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USAAMRDL-TR-76-29

LOW-EMISSIONS COMBUSTOR DEMONSTRATION

Detroit Diesel Allison Division
General Motors Corporation
Indianapolis, Ind. 46206

March 1977

Final Report for Period 1 March 1974 - 31 December 1975

Approved for public release;
distribution unlimited.

Prepared for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
Fort Eustis, Va. 23604

EUSTIS DIRECTORATE POSITION STATEMENT

The work reported herein represents the application of recent low-emission technology to an aircraft gas turbine engine. The latest emission abatement concepts are applied and the results documented in actual engine testing. It is expected that the design procedures described herein will be used in the design of low-emission combustors for future Army aircraft. Appropriate technical personnel of this Directorate have reviewed this report and concur with the conclusions and recommendations contained herein.

Mr. Robert G. Dodd and Mr. Kent F. Smith of the Propulsion Technical Area, Technology Applications Division, served as Project Engineers for this effort.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objectives of this eighteen-month program were to further develop two low-emission combustors—the prechamber combustor and the modified conventional combustor—which had previously demonstrated low emissions in USAAMRDL Contract DAAJ02-72-C-0005, to install them in a Detroit Diesel Allison Model 250-C20B engine, and to evaluate their performance in an engine environment. The combustors were to retain the 50% overall reduction in

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gas turbine mass emissions ($CO+CH_x+NO_x$) with no increase in any individual pollutant when tested over a typical Army light observation helicopter (LOH) duty cycle.

The program was conducted in four general tasks:

- Task I - Combustor Development and Rig Testing
- Task II - Baseline Combustor Engine Testing
- Task III - Low-Emissions Combustor Engine Testing
- Task IV - Data Analysis

In Task I, the prechamber and the modified conventional low-emission combustors were concurrently developed in a series of combustor rig tests to improve their exhaust temperature profiles, durability, stability, ignition characteristics, and pressure losses, while maintaining their emissions abatement and low-smoke characteristics.

Task II documented the baseline combustor performance and Task III evaluated each low-emissions combustor developed in Task I on a DDA Model 250-C20B turboshaft gas turbine engine. The prechamber combustor was tested for exhaust temperature profile, cyclic durability, and exhaust emissions on JP-4, JP-5, and an oil shale fuel refined toward a JP-5/Jet-A specification. The modified conventional combustor was engine tested to assess exhaust temperature profile and exhaust emissions from JP-4 fuel.

In Task IV, data reductions and analyses were carried out and combustor rig and engine performance with combustors were correlated, and the effects of the low-emissions combustors on engine performance were determined.

Both low-emission concepts demonstrated significant reductions in exhaust emissions when compared with the base-line combustor, although neither combustor completely met all of the emissions goals. Combustor exhaust temperature profile and liner durability were adequate, causing no engine damage or liner failures after more than 92 engine test hours covering the full range of engine operation.

PREFACE

The author is grateful for the significant contributions made to the program by other Detroit Diesel Allison (DDA) personnel. Messrs. F. J. Verkamp, J.G. Tomlinson, and R. E. Sullivan provided technical guidance throughout the program. Dr. D.W. Clark and Mr. C. L. Walker provided the direction and personnel for the rig testing of the development combustors. Mr. J. R. Williams conducted the combustion laboratory operations for acquiring and reducing the combustor performance. Mr. W.H. Roberts was responsible for expediting the fabrication of the combustor hardware. Mr. W.F. Egbert supplied a Model 250-C20B engine for use in the engine testing of the low emissions combustors and also provided technical support personnel from his Model 250 (T63) Project Group. Mr. W. R. Stiefel provided the direction and personnel for the engine testing. Mr. E.A. Oprisu was responsible for conducting the engine tests. Mr. R. L. Johnson provided the personnel and equipment for the engine emissions measurements.

An independent analysis of a sample of oil-shale-derived fuel was supplied by Senior Research Engineer Clifford A. Moses of the U.S. Army Fuels and Lubricants Research Laboratory, San Antonio, Texas.

The author is also grateful for the program guidance, suggestions, and technical support provided by Messrs. R.G. Dodd and K.F. Smith of the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory.

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INTRODUCTION

Measurements made on various gas turbine engines show that the major air pollutants emitted from these engines are carbon monoxide (CO) and unburned hydrocarbons (CH_x) at low power settings, and oxides of nitrogen (NO_x) and smoke at high power. The causes of these pollutants are known, being combustion inefficiency plus quenching effects in the case of CO and CH_x, and high average and local flame temperatures in the case of NO_x. The cause of smoke (particulate emissions) is fuel-rich, droplet combustion (a carbon formation problem) and the quenching of carbon oxidation reactions prior to consumption (carbon consumption problem). It is therefore not difficult to conceive of alterations to the combustion, cooling, and dilution processes performed in the gas turbine combustor which would result in significantly reduced mass emissions.

Past emission abatement efforts in aircraft gas turbine engines have been directed primarily toward the elimination of visible pollution—smoke. Future aircraft emission regulations will also require the control of non-visible emissions—carbon monoxide, hydrocarbons, and nitrogen oxides over a specified aircraft duty cycle. U.S. Public Law 91-604, "Clean Air Amendments of 1970," which was approved 31 December 1970, directed the Environmental Protection Agency (EPA) to establish aircraft pollution standards. In response to this directive the EPA published in the Federal Register emissions standards, compliance dates, and test procedures for commercial aircraft and aircraft engines.[1] In general, these regulations require significant reductions in all mass emissions.

In addition to the ecological incentive for low-mass-emission combustors, there are many other potential benefits for low-emission combustion systems, such as

- Noise reduction
- Altitude ignition improvement
- Specific fuel consumption reduction
- Increased combustor life due to decreased liner temperature with reduced flame radiation
- Longer turbine section life due to reduced erosion

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[1] Federal Register, Vol 38, No. 136, Tuesday, July 17, 1973, Title 40—Protection of Environment, Chapter 1—Environmental Protection Agency, Part 87—Control of Air Pollution from Aircraft and Aircraft Engines.

In 1971-72 Detroit Diesel Allison (DDA) conducted a 12-month program under Army contract to develop emission abatement technology for aircraft gas turbine engine combustors. Using the 317 hp turboshaft T63-A-5A engine as the baseline, various emission reduction concepts were investigated both analytically and experimentally. Two combustors resulted from the extensive combustor rig testing, the prechamber combustor and the modified conventional combustor (Figure 1). Both combustors demonstrated sufficient emission abatement technology for achieving the program goals of a 50% reduction in total emissions ($CO + CH_x + NO_x$) over the duty cycle of a light observation helicopter (LOH) while allowing no increase in individual pollutants. This duty cycle is shown in Figure 2.

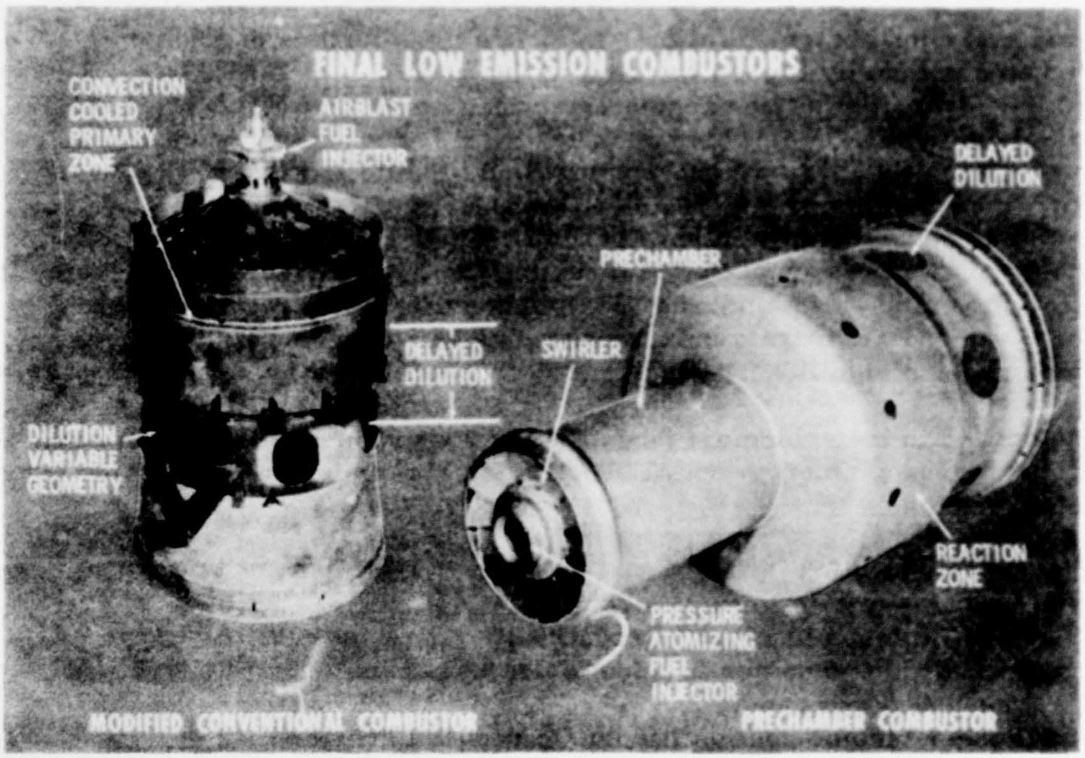

Figure 1. Final Combustors Produced for an Army Low-Emission Technology Generator Contract.

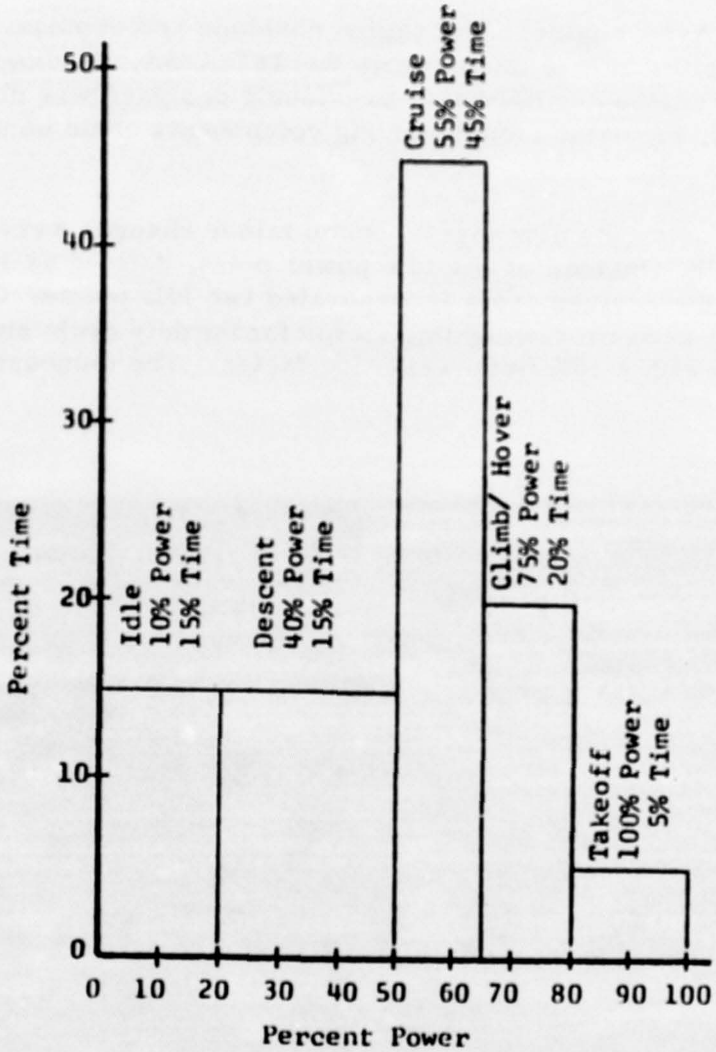

Figure 2. Composite T63-A-5A Army LOH Duty Cycle.

In 1974 the program reported herein was initiated with the overall objective of demonstrating the performance of both low-emission combustor concepts in a series of dynamometer engine tests. Because the Army helicopter power requirements would be increasing in the future, it was decided to utilize the next generation T63 type engine in this program, the Model 250-C20B, which has a take-off rating of 420 hp, a 25% increase in power

over the T63-A-5A engine. The engine envelope and combustion system of the Model 250-C20B is the same as the T63-A-5A, as shown in Figure 3. Thus, the combustor hardware previously designed was directly adaptable. In fact, the same combustor rig components could be used for development work.

In addition to using the new engine, some minor changes were made to the LOH duty cycle. Instead of one idle power point, defined as 10% of maximum power, the revised cycle incorporated two idle points: Ground idle at 5 shp with a zero time-weighting factor for the duty cycle and operational idle at 25 shp with a 15% time-weighting factor. The combustor operating

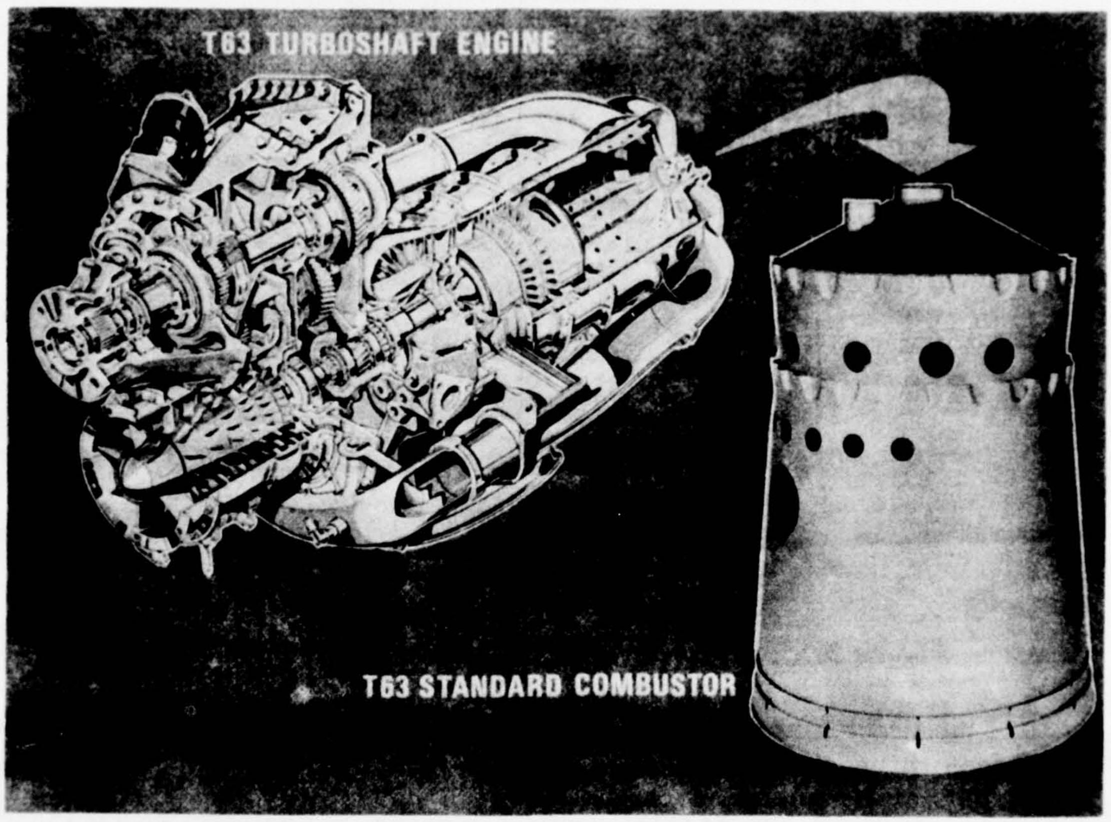

Figure 3. Model 250/T63 Engine and Combustion Liners.

conditions for the Model 250-C20B engine, including the LOH duty cycle points, are shown in Table 1. The duty cycle is shown in Figure 4. Both of the nontime-weighted cycle points were used to help define emission levels at the low end of the power range, where large changes typically occur.

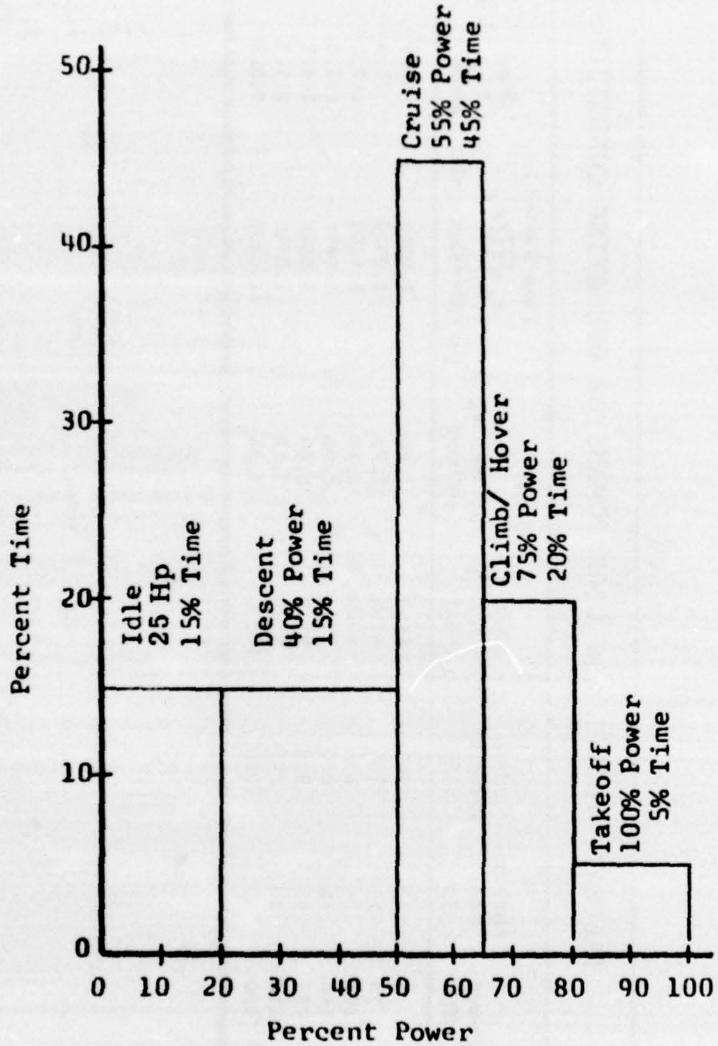

Figure 4. Composite Model 250-C20B Army LOH Duty Cycle.

TABLE 1. MODEL 250-C20B COMBUSTOR OPERATING CONDITIONS

Engine (%)	Power (HP)	Time in Mode (%)	Inlet Temp T_3 (°R)	Inlet Press., P_3 (Psia)	Airflow, W_a (lb/sec)	Flow Factor $W_a \sqrt{T_3}/P_3$ (lb °R$^{1/2}$/sec-psia)	Fuel Flow (lb/hr)	Fuel-Air Ratio	Combustor Exit Temp (°R)
Grd. Idle	5	-	745	41.0	1.55	1.0319	62.5	.0112	1500
Opr'l. Idle	25	15	765	45.5	1.70	1.0334	71.6	.0117	1578
25	105	-	835	60.0	2.16	1.0403	107.3	.0138	1765
40	168	15	885	71.0	2.50	1.0475	135.0	.0150	1880
55	231	45	925	81.5	2.80	1.0449	164.3	.0163	2000
75	315	20	975	93.5	3.12	1.0419	211.2	.0188	2195
100	420	5	1030	105.0	3.35	1.0239	265.3	.0220	2415

The program was conducted in four tasks:

- Task I - Combustor Development and Rig Testing
- Task II - Baseline Combustor Engine Testing
- Task III - Low Emissions Combustor Engine Testing
- Task IV - Data Analysis

The objective of Task I—Combustor Development—was to define the Model 250-C20B operating conditions which could be used on the combustor test rig, define the acceptance criteria for the low-emission combustors, test the baseline combustor to document performance, and develop both low-emission combustors to try to achieve the performance goals defined by the acceptance criteria. The Model 250-C20B operating conditions are shown in Table 1. The performance acceptance criteria for the low-emission combustor are shown in Table 2. These criteria were a 50% reduction in total emissions and specified reductions in constituent pollutants. Exhaust smoke was limited to a 35 SAE/EPA smoke number. Maximum levels were defined for exhaust temperature pattern, pressure drop, and liner metal temperature so that the liners would be engine-worthy for the evaluations in Task III. Combustor size was also restricted to the baseline case diameter and a 3.0-inch case length increase.

The combustor rig development of the prechamber and modified conventional combustor liners constituted the majority of the effort expended in Task I. Thirteen versions of the prechamber and ten versions of the modified conventional liners were tested on the combustor rig. These individual tests are discussed in the next section, COMBUSTOR DEVELOPMENT. During Task I, a total of 307 data points were recorded during 95:09 burning hours. A total of 2003 gal of JP-4 fuel were used. A series of thermal paint liner-metal temperature tests and simulated altitude and ambient starting tests on each combustor completed the combustor rig testing.

Tasks II and III were concurrent tests, using reference-grade JP-4 fuel, in which the baseline and each low-emission combustor were tested on a specification quality Model 250-C20B engine. In Task II, the baseline production combustor hardware was tested for exhaust temperature pattern, liner metal temperatures, engine performance, and exhaust emissions, to form the engine characteristics against which the low emission combustor systems could be compared. In Task III, the prechamber and modified conventional combustors were engine tested for performance, exhaust temperature pattern, and exhaust emissions. In addition, the prechamber combustor was subjected to a 40-hour cyclic durability test and performance and exhaust emissions were measured when the engine was

TABLE 2. MODEL 250-C20B LOW EMISSIONS COMBUSTOR PERFORMANCE ACCEPTANCE CRITERIA

PARAMETER	LOW EMISSIONS COMBUSTOR ACCEPTANCE CRITERIA	EXISTING ENGINE DATA
Emissions:		
C_3H_8	Max LOH EI 50% baseline	--
CO	Max LOH EI 50% baseline	--
NO_x	Max LOH EI 90% baseline	--
C_3H_8+CO+NO_x	Max LOH EI 50% baseline	--
Smoke Number	35 Maximum	--
Exhaust Temp. Profile:		
Pattern Factor	.25 Maximum	.14
T_{max}/T_{avg}	1.18 Maximum	1.10
Pressure Drop	5.0%	3.75%
Max. Liner Temp.	1700°F	1700°F
Stability, LBO at Idle	Equal to Baseline	--
Ignition System	Existing C20B	--
Size:		
Combustor Case ID	Existing C20B Diameter	--
Combustor Case Length		
Goal	Max of 3" longer than baseline	--
Max Allowable	Max of 5" longer than baseline	--

operated on JP-4 regular, JP-5 regular, and oil shale derived JP-5/Jet-A fuels. These data are discussed in the final section, ENGINE TESTING.

The reduction of the test data, the rig to engine correlations, and the combustor to engine correlations were conducted in Task IV—Data Analysis. These results are included in the final section, ENGINE TESTING.

COMBUSTOR DEVELOPMENT

Combustor development was the first task conducted in the program. The two final combustors (shown in Figure 1 and which were from the previous emissions abatement programs) were returned to DDA so that additional combustor rig testing could be performed to improve the general performance of each combustor.[2] Both the prechamber and the modified conventional combustors had demonstrated the emission abatement goal of a 50% total emissions reduction ($CO+CH_x+NO_x$) in a rig test with no increase in any constituent above baseline levels. What remained was the maintaining of these low-emission levels in an actual engine with uprated conditions from the T63 turboshaft engine, the Model 250-C20B, while improving combustor exhaust temperature profile, lightoff and altitude performance, and reducing liner pressure drop and metal temperatures.

First, a baseline combustor was rig tested at the Model 250-C20B combustor operating conditions to document exhaust emissions and combustor performance. Then, low-emission combustor development was conducted concurrently on the prechamber and the modified conventional combustors. Thirteen different prechamber combustor configurations and ten different modified conventional combustor configurations were rig tested. This rig testing resulted in 307 data points being recorded during 95:09 hours of burning, which consumed 2003 gallons of JP-4 fuel.

The final versions of each low-emission combustor configuration were further tested at ambient and at simulated 25,000-ft altitude conditions, to assess starting capabilities. Each combustor liner was also painted with a thermally sensitive paint and operated at 100% power, to define the temperature distribution on the liner metal.

The work conducted in each of these areas is discussed in the following sections.

EXPERIMENTAL SYSTEM

The combustor development tests were conducted in the DDA Combustion Research Laboratory using JP-4 regular fuel and non-vitiated (neat) air. The combustor operating conditions simulated by the rig were those of the Model 250-C20B gas turbine engine. The required operating conditions, previously defined in Table 1 vary over the following ranges:

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[2] Troth, D. L., Verdouw, A. J., and Verkamp, F. J. Investigation of Aircraft Gas Turbine Combustor Having Low Mass Emissions, Detroit Diesel Allison, Division of General Motors Corporation. USAAMRDL Technical Report 73-6, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, April 1973, AD764987.

Combustor inlet temperature	285° to 570°F
Combustor inlet pressure	41 to 105 psia
Fuel flow rate	62 to 265 lb/hr
Airflow rate	1.5 to 3.4 lb/sec.

The above combustor operating conditions could be readily simulated under steady-state conditions in the DDA Combustion Research Laboratory. Major elements of the facility used in conducting the experiments were:

- Air supply system
- Fuel supply system
- Ignition system
- Data acquisition and reduction system
- Emission measurement system
- T63 combustor test rig.

The systems and experiments were remotely operated from the control room shown in Figure 5. The above listed combustion facility elements are described in the following paragraphs.

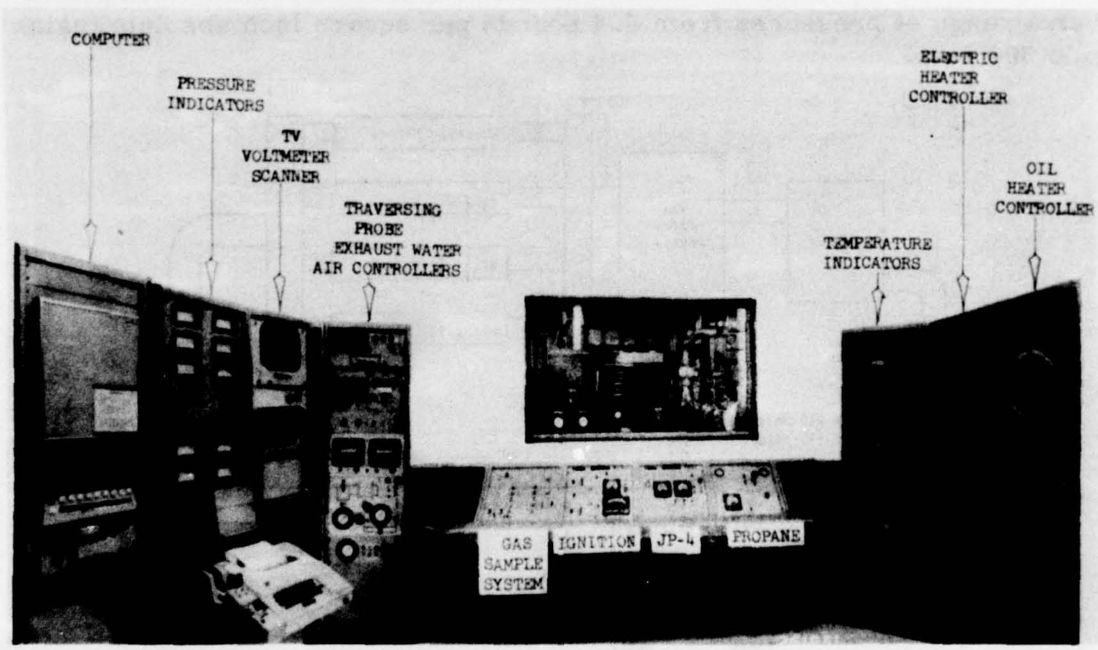

Figure 5. Combustion Research Laboratory Control Room.

Air Supply System

The air supply system provided nonvitiated air at the required inlet temperature, pressure, and flow rate to simulate the engine combustor airflow conditions. This system, as shown in Figure 6, include an air filter, air heaters, an airflow control, a pressure control, flow metering, and exhaust systems. After the air passed through a filter, the airflow was measured with a standard ASME flange-tap orifice plate. A throttling valve controlled the airflow rate. An oil-fired Thermal Research air heater and a bank of four electric heaters in parallel, rated at 200 kw each, were used to heat the combustor inlet air temperatures. This heater system is capable of heating the inlet air to 1500°F. However, in this program, the maximum required temperature was 570°F.

The test facility can accommodate two 150-inch-long test sections. Test section connections are made with 10-inch flanges at the inlet and exhaust. In this program, the T63 test rig was installed in one of the 150-inch test sections. The exhaust ducting is equipped with an automatic water spray bar system for cooling the exhaust products to 450°F. The exhaust gas is then either vented to the atmosphere or ducted through a set of steam ejectors. With this system, the test section static pressure can be controlled over a range of pressures from 4.4 pounds per square inch absolute (psia) up to 300 psia.

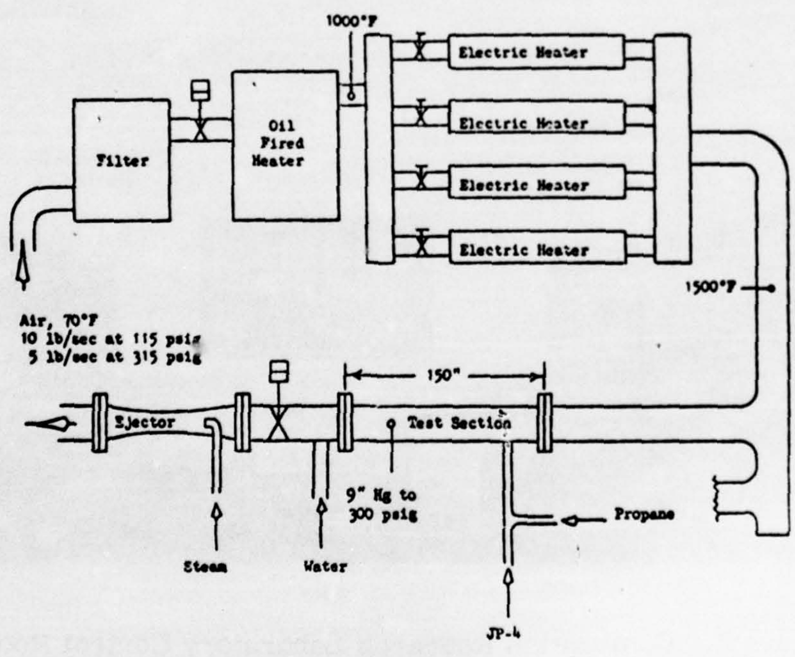

Figure 6. Combustion Research Facility Air Supply Schematic.

Altitude simulation was required in this program and the test section pressure was controlled from a minimum of 5.45 psia (25,000 ft equivalent pressure) to 105 psia at 100% power sea level standard (SLS) conditions for the Model 250-C20B engine.

Fuel Supply System

All the combustor liners in this program were rig tested on JP-4 fuel. The JP-4 system is capable of supplying fuel at a maximum flow rate of 2450 lb/hr and a maximum pressure of 2000 psia. These were more than adequate to meet the fuel flow requirements of this program. The JP-4 was stored in an underground tank and transferred by a boost pump to a high pressure pump which could provide a maximum delivery pressure of 2000 psia. The JP-4 fuel system incorporates a surge tank and feedback system to eliminate any potential pressure pulsations in the fuel flow delivery. JP-4 flow rates were measured with a turbine-type flowmeter which had been calibrated on JP-4 fuel.

Ignition System

Because the developed versions of each low-emission combustor were to be evaluated by engine testing, the production Model 250-C20B ignition system was used for all of the rig development testing. Thus, a 24 volt power source was connected to the production engine capacitive discharge exciter, production igniter cable, and surface gap sparkplug. The production spark plug was used for baseline combustor testing and for the modified conventional combustor testing since each liner used the same dome configuration and thus the same igniter installation. The prechamber combustor used a side mounted igniter, and thus this igniter was considerably longer.

Data Acquisition and Reduction System

An automatic digital data acquisition and reduction system was used in this program. The system can acquire 200 channels of input tèst data in 15 seconds. The principal components of the digital data acquisition system are a cross-bar scanner, a digital voltmeter, a digital computer, a high-speed paper tape reader, a teletype printer, and a high-speed paper tape punch. The digital data acquisition system operates as follows:

- The scanner (as programmed by the computer) steps through the 200 data channels and feeds the signals to the voltmeter. The only restriction is that the input data must be in the form of either voltage or frequency.

- The digital voltmeter reads the signals as received and sends them sequentially to the computer.
- The digital computer reduces the raw data to engineering units, such as pressure and temperature. The computer also uses the data to calculate the desired flow parameters, such as airflow rate, fuel flow rate, fuel-air ratio, percent pressure drop, and emission indices.
- The calculated data are then printed out by the teletype and are logged by the high-speed punch.

The *cross-bar scanner* is a Hewlett-Packard 2911A/B, 200-channel unit. The voltmeter is a Hewlett-Packard 2402A integrating digital voltmeter. The computer is a Hewlett-Packard Model 2116B with 16,000 words of memory. The computer is equipped with a high-speed paper-tape reader.

A data acquisition computer program was written for these tests to acquire electrical signals from the various types of instrumentation and convert those signals to the corresponding engineering units. Once converted, these data were used in the data reduction program to calculate parameters, such as fuel flow, airflow, fuel-air ratio, emission indices, pressure loss, temperature profile, temperature pattern factor, and other parameters of interest.

Data reduction calculations for some parameters such as combustion efficiency, chemical fuel-air ratio, exhaust emission concentrations, and emission indices—relied wholly or in part on measured concentrations of exhaust gases.

The combustion efficiency was calculated from the exhaust gas analysis data, using the following equation:[3,4]

$$\eta_b = 1 - \frac{fr_{CO}(-121,745) + fr_{CH_x}(-879,347) - fr_{NO}(38,880) - fr_{NO_2}(14,554)}{(fr_{CO} + fr_{CO_2} + 3\,fr_{CH_x})\ (A)} \quad (1)$$

[3] Hardin, M.C. Calculation of Combustion Efficiency and Fuel-Air Ratio from Exhaust Gas Analyses. RN 73-48. Detroit Diesel Allison, Division of General Motors Corporation, P.O. Box 894, Indianapolis, Indiana. July 1973.

[4] Hardin, M.C. Estimation of the Heat of Combustion and Hydrogen Content of Liquid Petroleum Fuels. RN 73-62. Detroit Diesel Allison, Division of General Motors Corporation, P.O. Box 894, Indianapolis, Indiana. October 1973.

The chemical fuel-air ratio was calculated as (1) a check on the fuel and airflow rate measurements and (2) a check on the emission gas sampling method to ensure that a valid sample is obtained from the exhaust. The chemical fuel-air ratio in hydrocarbon fuel-air reactions was calculated from wet basis exhaust gas analysis, using the following equation:

$$F/A = \frac{(fr_{CO_2} + fr_{CO} + fr_{CH_x})\,(B)}{0.21 - (fr_{CO_2} + fr_{CO} + fr_{CH_x})\,(B)} \tag{2}$$

In the preceding equations, fr_{xx} is the volume fraction of the component as reported by gas analysis. The subscript CH_x stands for unburned hydrocarbons, reported as CH_4. The values of constants (A), (B), and (C) are listed in Table 3 for the JP-4 fuel.

TABLE 3. FUEL CONSTANTS FOR CALCULATION OF COMBUSTION EFFICIENCY AND FUEL-TO-AIR RATIO

Fuel	Fuel Constants A	B	C
JP-4	263,070	0.10154	0.9910

The emission indexes (EI) for carbon monoxide, hydrocarbons, and oxides of nitrogen were calculated, using the following equations.

$$EI_{CO} = \frac{28.011\, C_{CO}\,(1 + F/A)}{28,970\ F/A} \tag{3}$$

$$EI_{CH_x} = \frac{44.097\, C_{CH_x}\,(1 + F/A)}{28,970\ F/A} \tag{4}$$

$$EI_{NO_x} = \frac{46.008\, C_{NO_x}\,(1 + F/A)}{28,970} \tag{5}$$

The volumetric concentration (C) in parts per million of NO_x used in the above equation, was the sum of NO and NO_2 as measured by the NDIR and NDUV instruments, or as NO_x when directly measured by the chemiluminescent analyzer.

Emission Measurement System

Most of the emission measurements were made on-line, using the following instruments and range sensitivities.

Sample	Instrument
Carbon monoxide (CO)	Beckman Model 315BL NDIR (0-100 ppm to 0-5000 ppm)
Carbon dioxide (CO_2)	Beckman Model 315B NDIR (0-5% and 0-25%)
Oxygen (O_2)	Beckman Model 715 Electrochemical Transducer (0-5% and 0-25%)
Nitric oxide (NO)	Beckman Model 315AL NDIR (0-150 ppm to 0-1500 ppm)
Nitrogen dioxide (NO_2)	Beckman Model 255 (long path) NDUV (0-100 ppm to 0-2500 ppm)
Total nitrogen oxides (NO_x)	Air Monitoring, Inc., Chemiluminescent Analyzer with NO_2 converter (0-1 ppm to 0-1000 ppm)
Unburned hydrocarbons (H/C)	Beckman Model 402 THC Analyzer (FID) (0-2 ppm C_3 to 0-10,000 ppm C_3)
Smoke	SAE-ARP 1179 system

The on-line emission analysis system was unique in design and instrumentation. The system consisted of two units: an analyzer console and a control console. To maintain minimum sample-transport time, the analyzer console was located in the test cell. The analyzer console, shown schematically in Figure 7, contained the actual gas analysis instrumentation and was electronically connected to the amplifier/readout units in the control console located in the control room (Figure 5). In addition to the readout units, the control console provided flow control to the analyzer and the sample bypass.

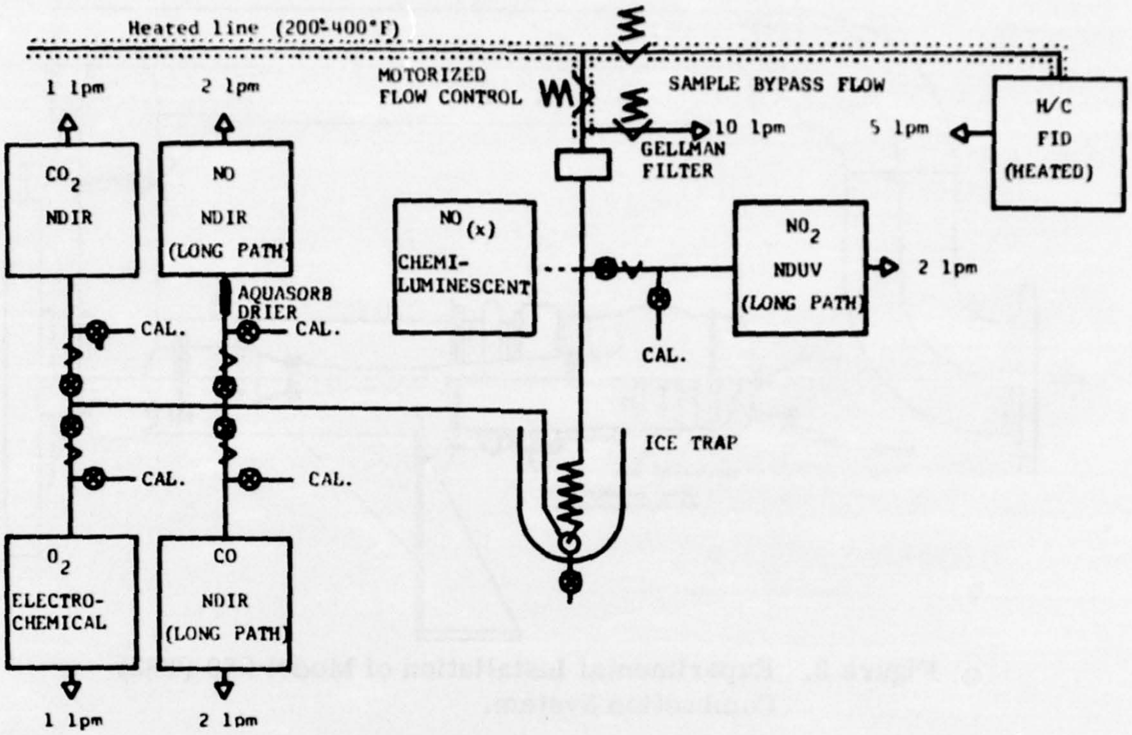

Figure 7. On-line Emission Analysis System Schematic.

The gas sample line from the test section to the analyzer console was Teflon-lined, stainless-steel tubing heated to 375°F. Suitable filters, condensers, and driers were provided in the analyzer console to assure accurate measurements.

The on-line instruments were calibrated through the use of calibration gases. Gases were normally available to provide five calibration points per analyzer range. The actual gas concentrations were determined by the vendor and checked by the DDA Physical Chemistry Research Section.

Two systems were used in this program to measure the NO_x emissions. Based upon experience in previous programs, it was concluded that, for concentrations of NO_x greater than 20 ppm, the NDIR plus NDUV instruments gave the most accurate data; and less than 20 ppm, the chemiluminescent instrument was the most reliable and accurate.

T63 Combustor Test Rig

All the combustors in this program were tested in a Model 250 combustor test rig as shown in Figure 8, which exactly simulated the flow path and

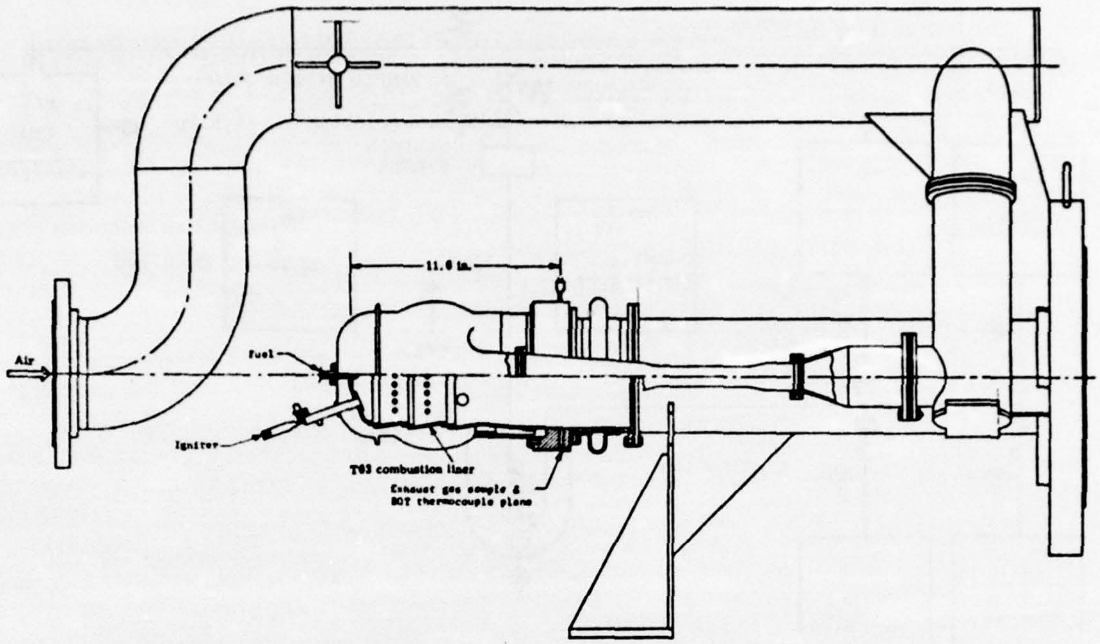

Figure 8. Experimental Installation of Model 250 (T63) Combustion System.

dimensions of the Model 250-C20B engine. The inlet air feed arms, the outer combustor case, and the turbine inlet section pieces were actual Model 250-C20B engine components.

In this program, the emissions were measured at the turbine inlet section as shown in Figure 9. Thirty-two ports were provided as shown to sample the combustor exhaust gas. These consisted of eight probes installed at equally spaced, circumferential locations, and each of the eight probes had four ports located radially to provide equal area sampling. The thirty-two ports all fed into a common manifold (outside) the rig. From the common manifold, the gases passed through the heated gas sample line to the analyzer console. In addition to the gas sample ports, the turbine inlet instrumentation plane contained two combustor outlet pressure probes, twenty-one C-A thermocouples, and four engine thermocouples as shown in Figure 9.

Throughout the program, visual observations of a liner's combustion pattern could be made by using the air-cooled periscope assembly shown in Figures 10 and 11. The view was obtained through a quartz window installed in the turbine inlet centerbody, directly upstream into the combustor liner. With this device, visual checks could be made of ignition processes, flame color and luminous intensity, asymmetrics in the reaction or intermediate zone flame patterns, or unusual aerodynamic phenomena created by liner design details.

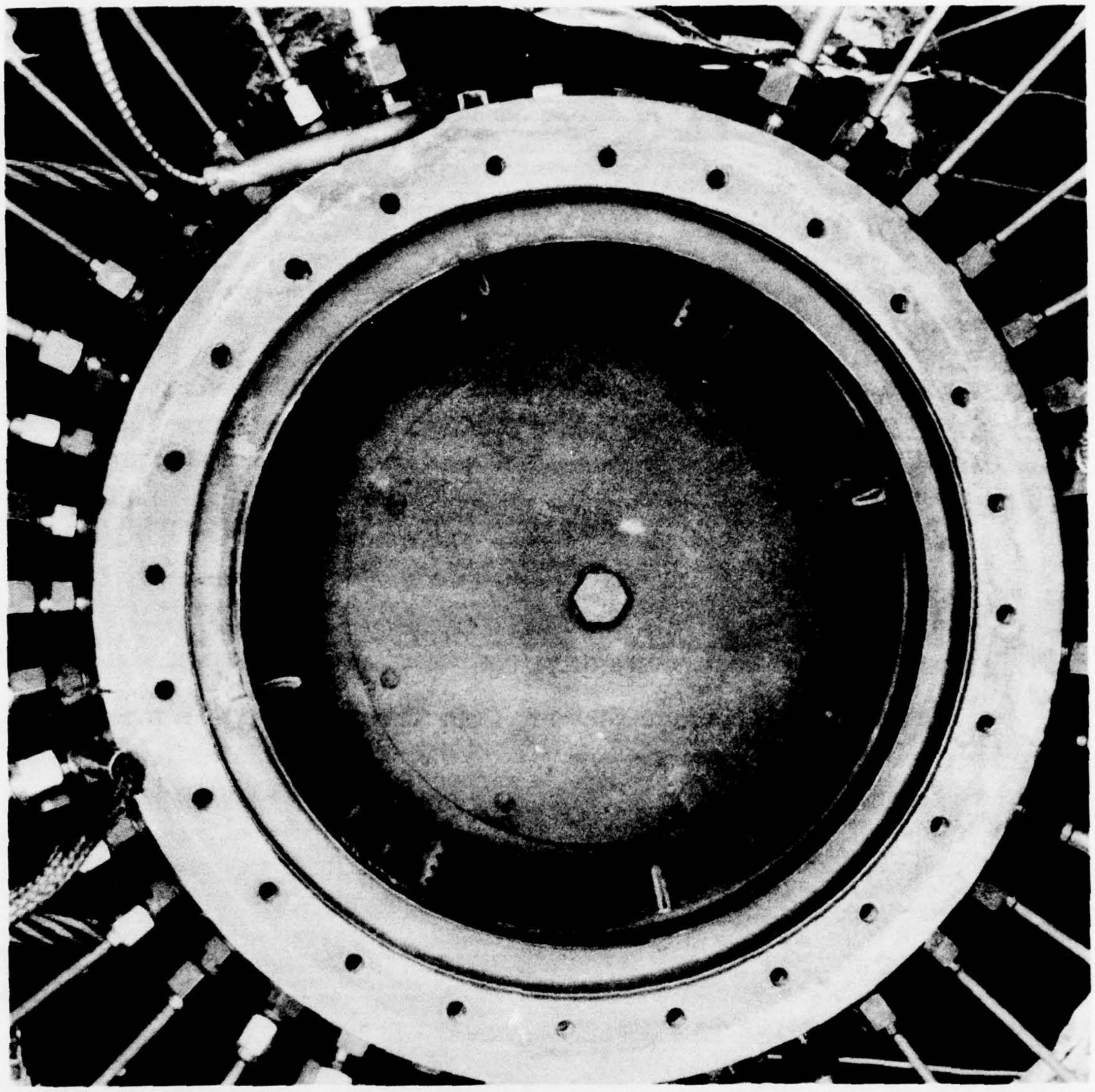

Figure 9. Combustor Rig Exhaust Instrumentation at Turbine Inlet Section.

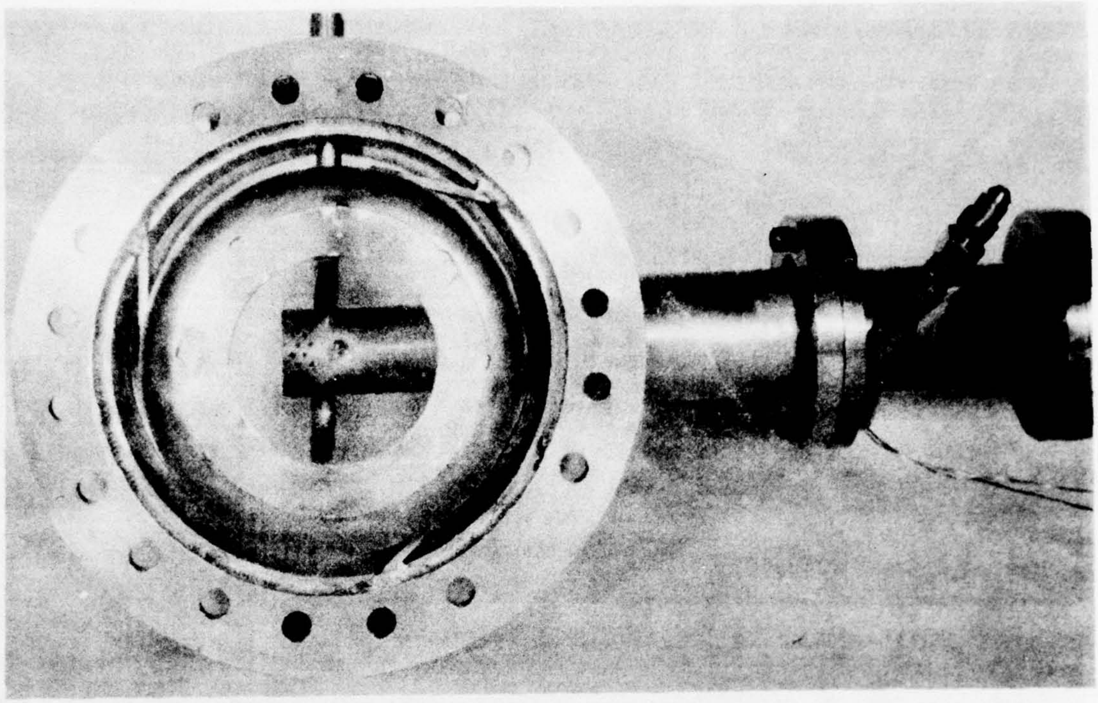

Figure 10. Periscope Viewing Path Through Quartz Window.

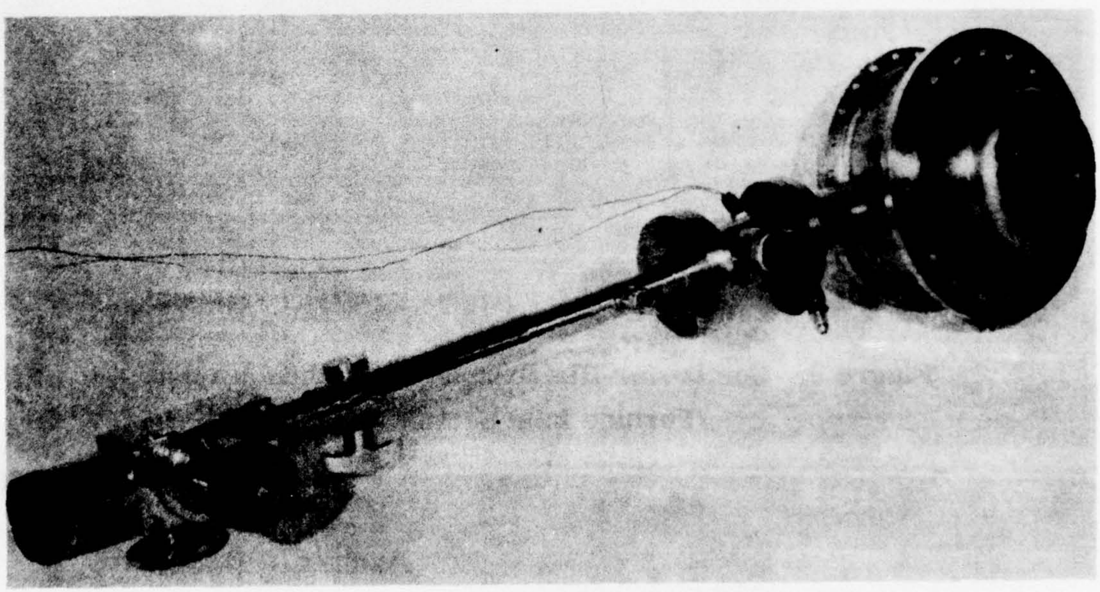

Figure 11. Periscope Assembly and Modified Turbine Inlet Centerbody.

BASELINE COMBUSTOR

The production Model 250-C20B gas turbine combustor liner was the baseline combustor liner used for this contract. The emissions of all low-emission combustor liners were compared with the emissions from this liner. The baseline Model 250 liner is shown in Figure 12. The production combustor system consists of a dual-orifice, pressure-atomizing fuel injector located in the center of the liner dome, a capacitive-discharge spark igniter located in the liner dome 1.25 inches off the liner axial centerline, and a "can" type film-cooled combustor liner. The combustor liner, shown in Figure 12, is 9.56 inches long overall. The liner has film cooling in the dome, one film-cooling annulus at the dome exit, and one final film-cooling annulus of identical geometry located 1.83 inches downstream from the first film-cooling annulus. Liner hole sizes and locations are summarized in Table 4. Using the dimensions in Table 4, the resulting liner airflow splits are tabulated in Table 5.

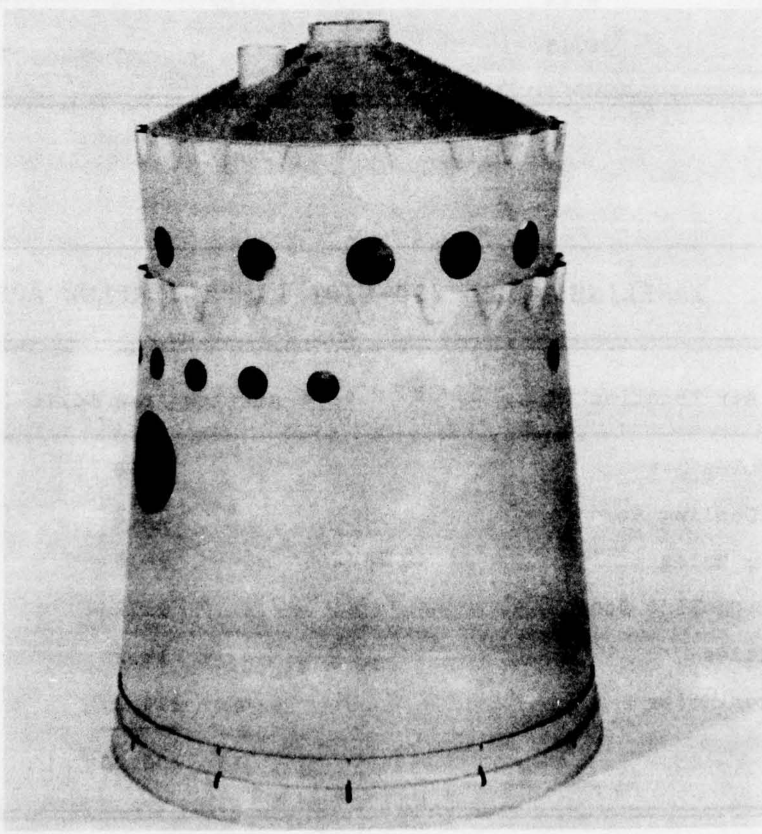

Figure 12. Baseline Model 250-C20B Combustor Liner.

TABLE 4. MODEL 250-C20B LINER DESIGN SUMMARY

Item	Axial Location From Dome Exit (in.)	Liner Dia. (in.)	Type Opening	Number	Size (in.)
Dome Cooling	-	1.74-4.66	Holes	54	.203 dia.
First Cooling Annulus	.0	5.31	Slots	22	.39 x .10
Primary	1.40	5.31	Holes	6 6	.562 dia. .500 dia.
Second Cooling Annulus	1.83	5.31	Slots	22	.39 x .10
Trim	2.89	5.52	Holes	14	.375 dia.
Dilution	4.14	5.70	Holes	2	1.250 dia.
Exit	8.19	6.21	-	-	-

TABLE 5. BASELINE MODEL 250-C20B LINER AIRFLOW AREA SPLITS

Inlet Air Location	Airflow Area Split (%)
Dome Holes	11.8
First Cooling Step	11.2
Primary Holes	26.4
Second Cooling Step	11.2
Trim Holes	15.2
Dilution Holes	24.2
	100.00

After a thorough shakedown of the Model 250 combustor rig installed in the DDA Research Combustion Test Facility, the Production Model 250-C20B combustor system was initially performance tested to document baseline aerodynamic and exhaust emission performance. Data were recorded at each of the steady-state light observation helicopter (LOH) duty-cycle operating conditions defined in Table 1. A summary of these data are presented in Table 6, showing exhaust emissions, gas analysis, and system performance from the combustor at each of the seven LOH operating conditions. The combustor liner was removed, painted inside and out with a thermally sensitive paint, identified as TP-6, reinstalled on the rig, and operated at takeoff combustor conditions to set the paint. Photographs of outside and inside surfaces of the liner are shown in Figures 13 through 16. The liner-metal temperatures were also measured with five thermocouples attached to the liner outside surface at the locations seen in the thermal paint photographs. Three of the thermocouples formed an axial line from the reaction zone to the liner exit. Two more thermocouples were located ± 120° from the dilution zone thermocouple to record temperatures in the axial plane of the dilution holes. A plot of these thermocouple metal temperatures is given in Figure 17. The thermal paint and the thermocouple temperatures agree quite well at the 100% or takeoff power condition.

Throughout this series of baseline tests, it was noticed that both the exhaust temperature profile and the liner metal temperatures from the thermal paint test showed a severe temperature unbalance. A plot of the individual temperatures in the combustor exhaust plane, Figure 18, showed a hot zone at the 1:30 circumferential position and cool temperatures throughout the remainder of the annulus. Normally both the 1:30 and 7:30 are hotter zones, with 4:30 and 10:30 quadrants being somewhat cooler.

Inspection of the baseline combustor components revealed no reason for the poor pattern, but an inspection of the combustor rig revealed that a sizeable crack had developed in the turbine inlet seal ring where the combustor connects to the turbine nozzle. This thermal fatigue failure was severe enough to require a teardown and the repair of the rig instrumentation section.

The production combustor system was then retested on the repaired combustion rig. This test was conducted at combustor conditions from operational idle to take-off and at the intermediate LOH duty cycle points. Detailed data sheets from these six test points are shown in Figures 19 through 24. These show burner inlet and outlet conditions, exhaust temperature survey data, inlet air tube and fuel conditions, liner metal temperatures, exhaust gas analysis parameters, and exhaust emissions. A

TABLE 6. COMBUSTION SYSTEM PERFORMANCE AT MODEL 250-C20B ENGINE CONDITIONS FOR THE PRODUCTION BASELINE COMBUSTOR (INITIAL RIG TEST)

	Idle		Percent Power				
	Grd.	Opr'l.	25	40	55	75	100
A. Emissions							
CO (ppm)	929.3	929.3	587.4	349.4	223.4	112.4	43.8
C_3H_8 (ppm)	130.0	100.0	34.0	9.8	2.0	1.1	1.1
NO_x (ppm NO_2)	16.1	22.2	32.0	35.1	43.4	59.3	91.1
Smoke Number	9.1	11.9	21.2	31.0	36.0	41.1	32.9
CO_2 (%)	2.06	2.45	2.85	3.06	3.31	3.79	4.38
B. Gas Analysis							
Comb. Eff. (%)	96.04	97.02	98.67	99.36	99.65	99.83	99.91
$F\text{-}A_{chem}/F\text{-}A_{mech}$	.920	1.008	1.020	1.019	.982	.960	.963
C. System Performance							
Pressure Drop (%)	3.94	3.59	3.64	3.29	3.58	3.61	3.41
T_{max}/T_{avg} (°F/°F)	1.249	1.243	1.223	1.186	1.177	1.190	1.135
Pattern Factor	.3516	.3333	.3124	.2671	.2535	.2693	.1928

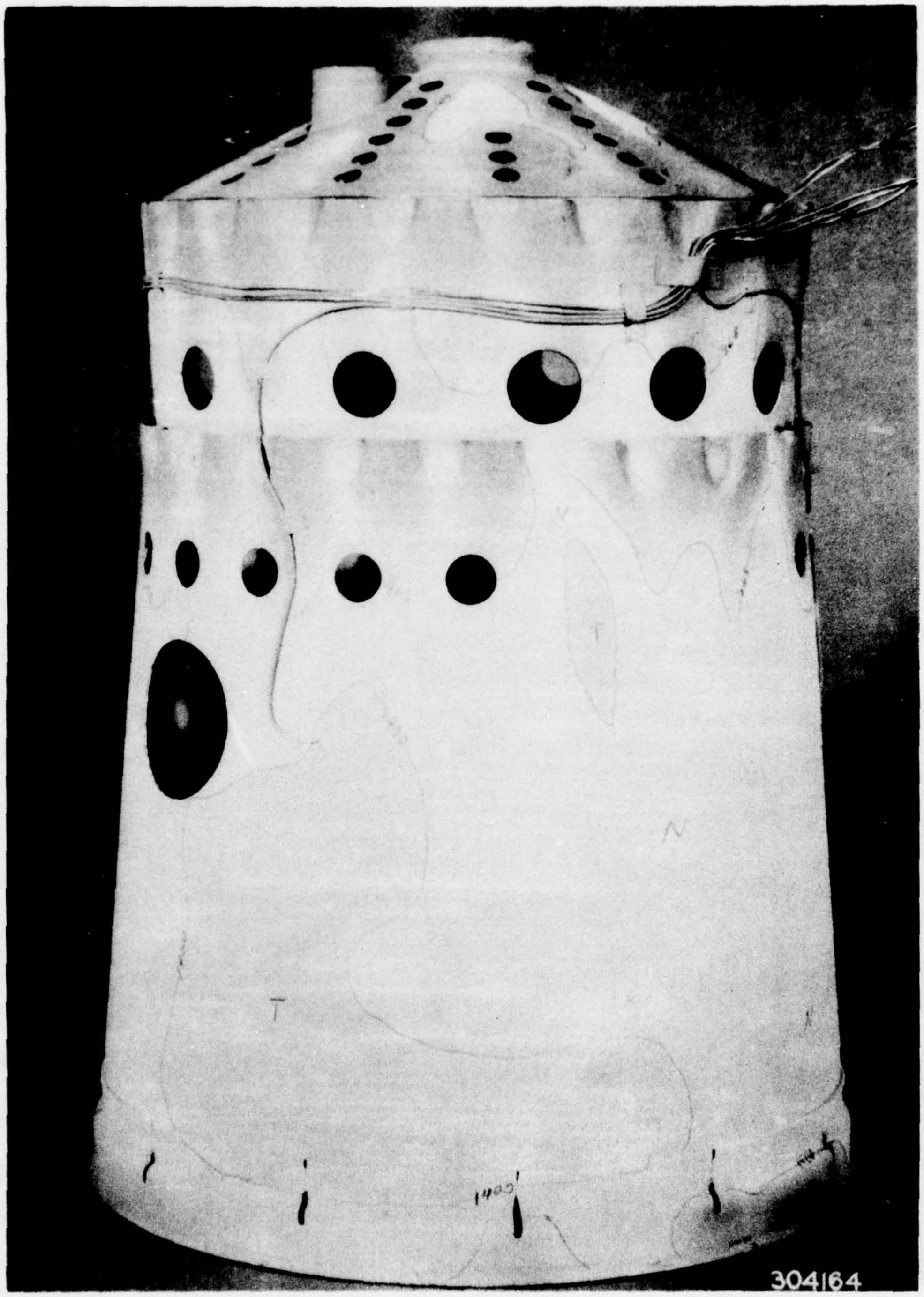

Figure 13. Baseline Liner Metal-Temperature Pattern at 100% Power, External 150°-270° Rotation.

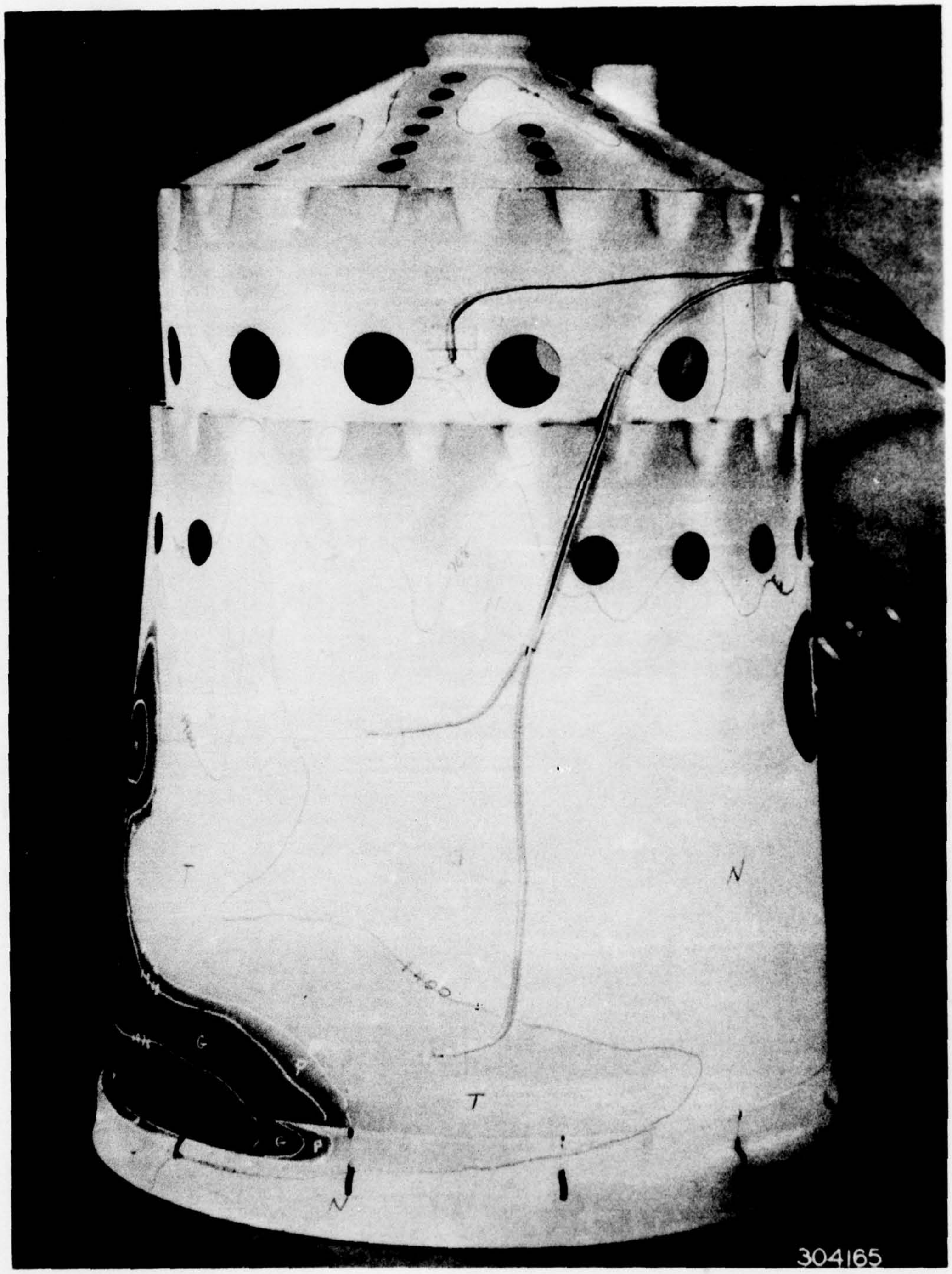

Figure 14. Baseline Liner Metal-Temperature Pattern at 100% Power, External 270°-60° Rotation.

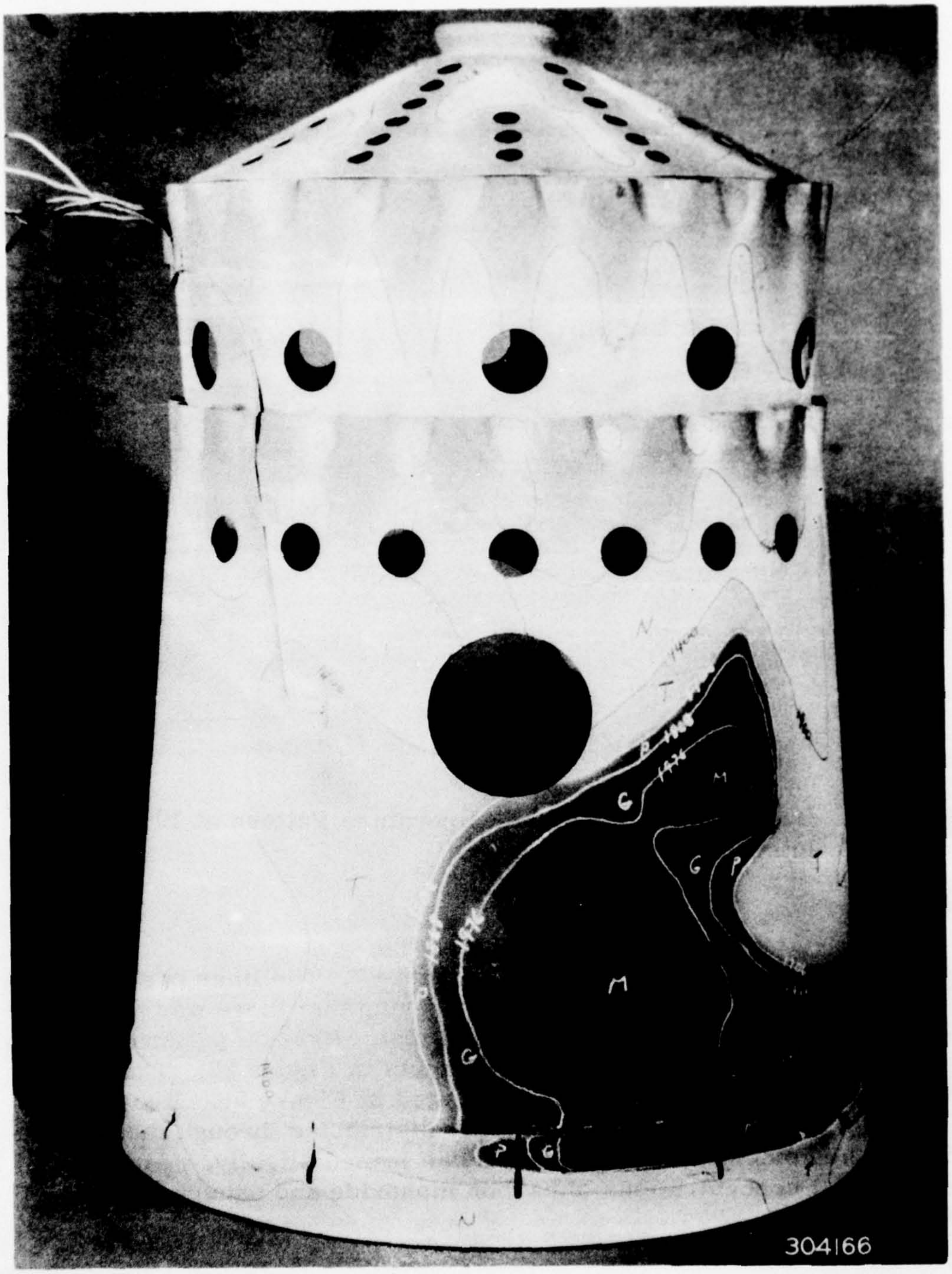

Figure 15. Baseline Liner Metal-Temperature Pattern at 100% Power, External 60°-150° Rotation.

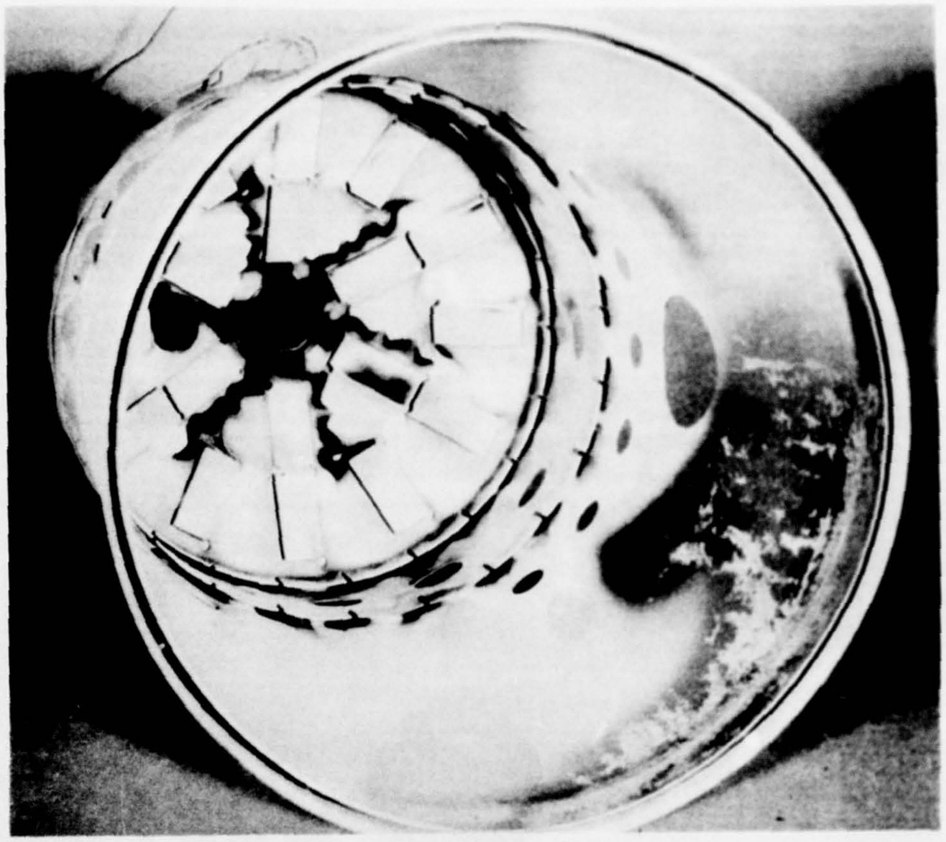

Figure 16. Baseline Liner Metal-Temperature Pattern at 100% Power, Internal.

summary of these data are presented in Table 7. The liner pressure drop increased at every operating condition, proving that there was significant leakage around the liner during the initial test. Exhaust pattern was also improved as shown by the pattern factor plots in Figure 25. The plot of individual exhaust temperatures is presented in Figure 26. Because the seal leakage in the initial test was evenly distributed through the combustor liner, the combustor primary zone was leaned slightly, resulting in higher exhaust concentrations of carbon monoxide and unburned hydrocarbons.

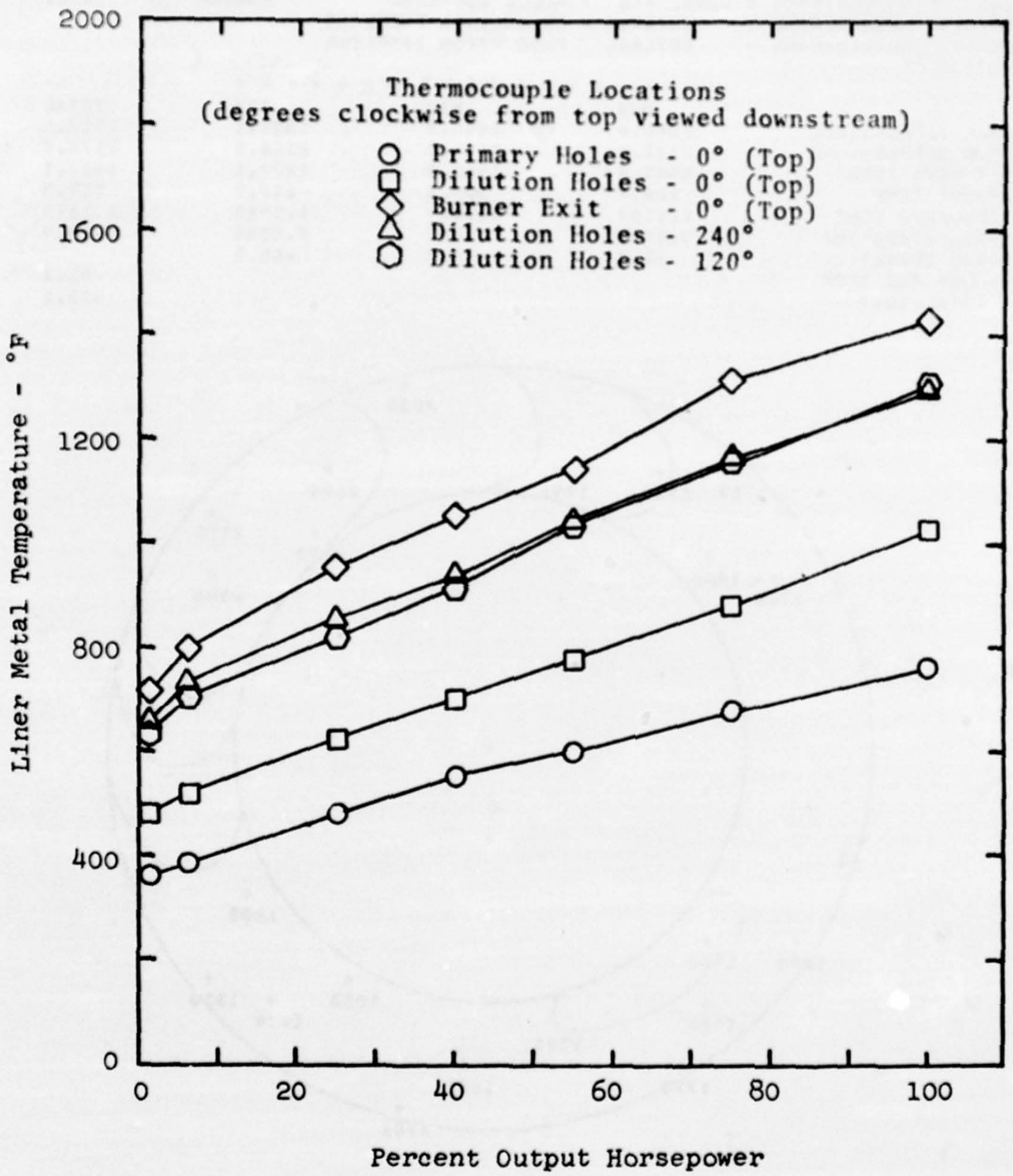

Figure 17. Baseline Liner Metal Temperatures, Initial Test.

PRODUCTION BASELINE COMBUSTOR RIG TEST (INITIAL) AT 100% POWER CONDITIONS
TEST DATE = 6-18-74 READING NUMBER = 1278 INLET TEMP = 575.
ENGINE NUMBER/NAME = COMB. RIG / MODEL 250-C20B ENGINE TOT = 1490.
OUTER CASE NUMBER/NAME = 6870992 / PRODUCTION BASELINE
LINER NUMBER/NAME = 6871486 / PRODUCTION BASELINE

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1943.3	1940.9	1852.1	1912.1
MAXIMUM TEMPERATURE	2170.0	2144.0	2116.0	2170.0
(AVG-INLET) TEMP	1368.3	1365.9	1277.1	1337.1
(MAX-AVG) TEMP	226.7	203.1	263.9	257.9
MAX TEMP/AVG TEMP	1.1167	1.1047	1.1425	1.1349
(MAX-AVG)/(AVG-IN)	0.1657	0.1487	0.2066	0.1929
(AVG-AVG TOTAL)	31.2	28.8	-60.0	
(TIP-HUB) AVG TEMP				-91.1
(AVG TOTAL-TOT)				422.1

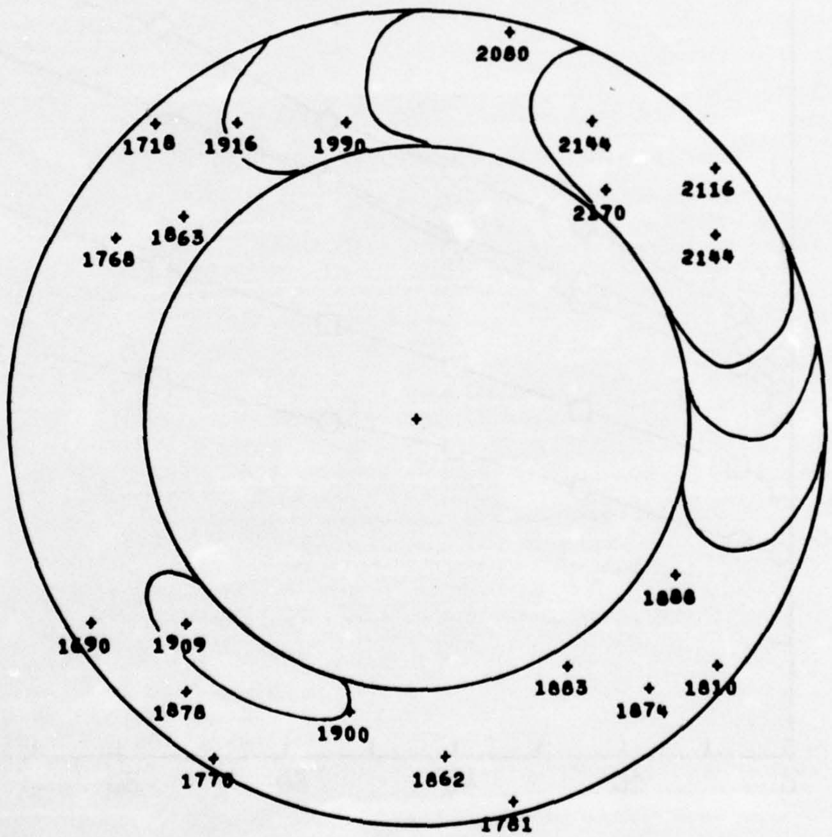

Figure 18. Baseline Liner Exhaust Temperatures at 100% Power, Initial Test.

```
         COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG 6/0 107, TEST SERIES -A  , READING #  1333
MODEL 250-C20B BASELINE LINER, P/N 6871486, NOZZLE S/N AG2032. JP4 FUEL.
TEST DATE: 06/18/74                            TIME OF DAY: 1259: 0 HOURS

CYCLE POINT  2                                          OPERATIONAL IDLE
************************* EXPERIMENTAL  CONDITIONS *************************
BURNER AIR FLOW          1.679 LB/SEC    AVG BURNER INLET TEMP   305. DEG F
AVG BURNER INLET PRES  45.2    PSIA      AVG BURNER OUTLET TEMP 1082. DEG F
AVG BURNER DELTA P      3.98    "HG      PRESSURE LOSS            4.32 %
OVERALL F/A RATIO      .01164  (F/M)     FUEL FLOW RATE          70.36 LB/HR
AIR LOAD FACTOR        1.0280            PATTERN FACTOR          .18605
BOT HOT SPOT:  # 37 = 1227.  DEG F       MAX BOT / AVG BOT       1.1336
FUEL INLET TEMPERATURE  94.  DEG F       FUEL INLET PRESSURE     192.0  PSIA
HEAT LOADING PARAMETER  .3376OE+07 BTU/HOUR/ATM/CUBIC FOOT (V=  .127315)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1144. 24 1081. 27 1129. 30 1101. 33 1046. 36 1059. 39 1216.
ANNULUS 2 22 1097. 25 1044. 28 1107. 31 1038. 34 1000. 37 1227. 40 1224.
ANNULUS 3 23  952. 26 1112. 29 1007. 32  879. 35  867. 38 1181. 41 1156.

 LEFT SIDE ************* AIR INLET TUBE CONDITIONS ************* RIGHT SIDE
TOTAL PRESSURE          45.15   PSIA    TOTAL PRESSURE           45.20   PSIA
AIR TEMPERATURE          305.   DEG F   AIR TEMPERATURE           305.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE......................... 14.33   PSIA

AIR FLOW DATA: P-REF= 119.7 PSIA   DELTA P= 1.15 "HG   T-REF= 100. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY      258.     HZ     VOLUMETRIC FLOW RATE  11.24 GAL/HR
FUEL PRESSURE AT F/M  344.8    PSIA     FUEL TEMP AT F/M          85.  DEG F
--------------------------------------------------------------------------
                        SKIN TEMPERATURE SURVEY:
 #44=  424. DEG F  #45=  614. DEG F  #46=  786. DEG F  #47=   91. DEG F
 #48=  823. DEG F  #
--------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .012468    COMBUSTION EFFICIENCY:  97.4075 %
 MEASURED CO2: 2.451 %   MEASURED O2: 18.60 %   CALCULATED O2: 17.49 %
ANALYSIS CHECK: F/A IS  .011850 WHEN CALCULATED USING MEASURED O2 VALUE
      -------------------------------------------------------------
                         EMISSIONS MEASUREMENTS
          CONCENTRATION  EMISSIONS INDEX          INSTRUMENT
               PPM        LB/1000 LB FUEL           SOURCE
      -------------------------------------------------------------
      CO    1081.36           90.677              BECKMAN NDIR
      CHX    174.31           23.062              BECKMAN  FID
      -------------------------------------------------------------
      NO       3.41             .471          AMI  CHEMILUMINESCENCE
      NOX     22.65            3.127          AMI  CHEMILUMINESCENCE
      -------------------------------------------------------------
      NO      10.82            1.494              BECKMAN NDIR
      NOX     22.28            3.076          BECKMAN  [NDIR + NDUV]
      -------------------------------------------------------------
         ABSOLUTE HUMIDITY = 26.28 GRAINS PER POUND OF DRY AIR
                SMOKE NUMBER = 11.12
```

Figure 19. Baseline Liner Rig Data at Operational Idle.

```
      COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG S/N 107, TEST SERIES -A  , READING #  1334
MODEL 250-C20B BASELINE LINER, P/N 6871486, NOZZLE S/N AG2032, JP4 FUEL.
TEST DATE: 06/18/74                           TIME OF DAY: 1325:14 HOURS

CYCLE POINT  3                                       25% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          2.157 LB/SEC    AVG BURNER INLET TEMP    375. DEG F
AVG BURNER INLET PRES   60.1    PSIA     AVG BURNER OUTLET TEMP 1317. DEG F
AVG BURNER DELTA P       5.21    "HG     PRESSURE LOSS               4.26 %
OVERALL F/A RATIO       .01381  (F/M)    FUEL FLOW RATE           107.28 LB/HR
AIR LOAD FACTOR         1.0373           PATTERN FACTOR           .19103
BOT HOT SPOT:  # 40 = 1497.   DEG F      MAX BOT / AVG BOT        1.1367
FUEL INLET TEMPERATURE  92.   DEG F      FUEL INLET PRESSURE      226.5  PSIA
HEAT LOADING PARAMETER  .38715E+07 BTU/HOUR/ATM/CUBIC FOOT (V=  .127315)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1381. 24 1314. 27 1342. 30 1353. 33 1285. 36 1315. 39 1471.
ANNULUS 2 22 1308. 25 1251. 28 1343. 31 1279. 34 1236. 37 1453. 40 1497.
ANNULUS 3 23 1156. 26 1325. 29 1320. 32 1108. 35 1067. 38 1451. 41 1407.

 LEFT SIDE ************* AIR INLET TUBE CONDITIONS ************* RIGHT SIDE
TOTAL PRESSURE          60.07    PSIA    TOTAL PRESSURE          60.07   PSIA
AIR TEMPERATURE         375.    DEG F    AIR TEMPERATURE         375.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................  14.24   PSIA

AIR FLOW DATA: P-REF= 119.1 PSIA   DELTA P= 1.91 "HG    T-REF=  97. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY        392.      HZ     VOLUMETRIC FLOW RATE  17.15 GAL/HR
FUEL PRESSURE AT F/M  352.0   PSIA     FUEL TEMP AT F/M            86.  DEG F
--------------------------------------------------------------------------
                        SKIN TEMPERATURE SURVEY:
 #44=  520. DEG F  #45=  755. DEG F  #46=  965. DEG F  #47=  100. DEG F
 #48= 1004. DEG F   #
--------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:   .014909    COMBUSTION EFFICIENCY:  98.5835 %
 MEASURED CO2: 3.029 %   MEASURED O2: 16.40 %   CALCULATED O2: 16.71 %
ANALYSIS CHECK: F/A IS  .013816 WHEN CALCULATED USING MEASURED O2 VALUE
      ----------------------------------------------------------------
                          EMISSIONS MEASUREMENTS
           CONCENTRATION  EMISSIONS INDEX          INSTRUMENT
               PPM        LB/1000 LB FUEL            SOURCE
      ----------------------------------------------------------------
       CO    786.12          55.784             BECKMAN NDIR
       CHX    76.28           8.521             BECKMAN  FID
      ----------------------------------------------------------------
       NO     12.93           2.144        AMI  CHEMILUMINESCENCE
       NOX    37.40           4.359        AMI  CHEMILUMINESCENCE
      ----------------------------------------------------------------
       NO     17.43           2.031             BECKMAN NDIR
       NOX    32.58           3.797        BECKMAN  [NDIR + NDUV]
      ----------------------------------------------------------------
        ABSOLUTE HUMIDITY = 26.28 GRAINS PER POUND OF DRY AIR
             SMOKE NUMBER = 20.80
```

Figure 20. Baseline Liner Rig Data at 25% Power.

```
      COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 107, TEST SERIES -A  , READING #  1335
MODEL 250-C20B BASELINE LINER, P/N 6871486, NOZZLE S/N AG2032, JP4 FUEL.
TEST DATE: 06/18/74                            TIME OF DAY: 1343:56 HOURS

CYCLE POINT  4                                        40% POWER SETTING
*********************** EXPERIMENTAL  CONDITIONS ***********************
BURNER AIR FLOW        2.542 LB/SEC    AVG BURNER INLET TEMP   423. DEG F
AVG BURNER INLET PRES  72.0    PSIA    AVG BURNER OUTLET TEMP 1437. DEG F
AVG BURNER DELTA P      6.21    "HG    PRESSURE LOSS             4.23 %
OVERALL F/A RATIO     .01510  (F/M)    FUEL FLOW RATE          138.17 LB/HR
AIR LOAD FACTOR       1.0484           PATTERN FACTOR           .18396
BOT HOT SPOT:  # 38 = 1624.  DEG F     MAX BOT / AVG BOT       1.1298
FUEL INLET TEMPERATURE  93.  DEG F     FUEL INLET PRESSURE      262.1  PSIA
HEAT LOADING PARAMETER  .41578E+07 BTU/HOUR/ATM/CUBIC FOOT (V=  .127315)

******************* BURNER OUTLET TEMPERATURE SURVEY *******************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1525. 24 1398. 27 1467. 30 1447. 33 1380. 36 1407. 39 1585.
ANNULUS 2 22 1467. 25 1378. 28 1482. 31 1392. 34 1344. 37 1601. 40 1611.
ANNULUS 3 23 1270. 26 1447. 29 1445. 32 1204. 35 1169. 38 1624. 41 1539.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE          72.02   PSIA    TOTAL PRESSURE           72.06   PSIA
AIR TEMPERATURE          423.   DEG F   AIR TEMPERATURE           423.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE......................  14.07   PSIA

AIR FLOW DATA: P-REF= 118.5 PSIA   DELTA P= 2.68 "HG    T-REF=  99. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       505.     HZ     VOLUMETRIC FLOW RATE  22.11 GAL/HR
FUEL PRESSURE AT F/M  369.6   PSIA     FUEL TEMP AT F/M           88.  DEG F
------------------------------------------------------------------------
                     SKIN TEMPERATURE SURVEY:
 #44=  591. DEG F  #45=  832. DEG F  #46= 1060. DEG F  #47=  112. DEG F
 #48= 1086. DEG F  #
------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .016071    COMBUSTION EFFICIENCY:  99.1057 %
 MEASURED CO2: 3.313 %   MEASURED O2: 17.80 %   CALCULATED O2: 16.34 %
ANALYSIS CHECK: F/A IS  .015040 WHEN CALCULATED USING MEASURED O2 VALUE
      ---------------------------------------------------------
                     EMISSIONS MEASUREMENTS
        CONCENTRATION  EMISSIONS INDEX       INSTRUMENT
             PPM        LB/1000 LB FUEL         SOURCE
      ---------------------------------------------------------
      CO     567.38         38.187           BECKMAN NDIR
      CHX     25.64          2.644           BECKMAN  FID
      ---------------------------------------------------------
      NO      26.41          2.820       AMI  CHEMILUMINESCENCE
      NOX     46.55          4.970       AMI  CHEMILUMINESCENCE
      ---------------------------------------------------------
      NO      26.18          2.795           BECKMAN NDIR
      NOX     38.53          4.114       BECKMAN  [NDIR + NDUV]
      ---------------------------------------------------------
       ABSOLUTE HUMIDITY = 24.08 GRAINS PER POUND OF DRY AIR
              SMOKE NUMBER = 27.03
```

Figure 21. Baseline Liner Rig Data at 40% Power.

```
        COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 107, TEST SERIES -A  , READING #  1338
MODEL 250-C20B BASELINE LINER, P/N 6871486, NOZZLE S/N AG2032, JP4 FUEL.
TEST DATE: 06/19/74                           TIME OF DAY: 1232:25 HOURS

CYCLE POINT  5                                         55% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          2.849 LB/SEC     AVG BURNER INLET TEMP   465. DEG F
AVG BURNER INLET PRES   80.1    PSIA      AVG BURNER OUTLET TEMP 1540. DEG F
AVG BURNER DELTA P       6.81    "HG      PRESSURE LOSS            4.18 %
OVERALL F/A RATIO      .01590  (F/M)      FUEL FLOW RATE         163.11 LB/HR
AIR LOAD FACTOR         1.0823            PATTERN FACTOR         .20103
BOT HOT SPOT:  # 38 = 1756.  DEG F        MAX BOT / AVG BOT      1.1403
FUEL INLET TEMPERATURE  86.  DEG F        FUEL INLET PRESSURE     292.3  PSIA
HEAT LOADING PARAMETER  .44170E+07 BTU/HOUR/ATM/CUBIC FOOT (V=  .127315)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
            ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1656. 24 1490. 27 1576. 30 1580. 33 1507. 36 1501. 39 1724.
ANNULUS 2 22 1574. 25 1497. 28 1566. 31 1486. 34 1463. 37 1701. 40 1739.
ANNULUS 3 23 1276. 26 1501. 29 1556. 32 1266. 35 1216. 38 1756. 41 1683.

 LEFT SIDE ************* AIR INLET TUBE CONDITIONS ************* RIGHT SIDE
TOTAL PRESSURE          80.02   PSIA    TOTAL PRESSURE           80.08   PSIA
AIR TEMPERATURE          465.   DEG F   AIR TEMPERATURE           465.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................  14.37   PSIA

AIR FLOW DATA: P-REF= 116.3 PSIA   DELTA P= 3.30 "HG    T-REF=  87. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       595.      HZ     VOLUMETRIC FLOW RATE  26.01 GAL/HR
FUEL PRESSURE AT F/M   384.8    PSIA      FUEL TEMP AT F/M         83.  DEG F
--------------------------------------------------------------------------
                        SKIN TEMPERATURE SURVEY:
 #44=  657. DEG F   #45=  903. DEG F   #46= 1149. DEG F   #47= 1124. DEG F
 #48= 1167. DEG F   #
--------------------------------------------------------------------------
       GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .010438     COMBUSTION EFFICIENCY:  99.4436 %
 MEASURED CO2: 3.417 %   MEASURED O2: 16.50 %   CALCULATED O2: 16.21 %
ANALYSIS CHECK: F/A IS  .014844 WHEN CALCULATED USING MEASURED O2 VALUE
     -------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
          CONCENTRATION  EMISSIONS INDEX        INSTRUMENT
               PPM        LB/1000 LB FUEL          SOURCE
     -------------------------------------------------------------
      CO      362.90           23.650            BECKMAN NDIR
      CHX       6.27             .605            BECKMAN  FID
     -------------------------------------------------------------
      NO       29.46            2.989        AMI  CHEMILUMINESCENCE
      NOX      51.64            5.239        AMI  CHEMILUMINESCENCE
     -------------------------------------------------------------
      NO       38.54            3.910            BECKMAN NDIR
      NOX      53.69            5.447        BECKMAN  (NDIR + NDUV)
     -------------------------------------------------------------
         ABSOLUTE HUMIDITY =  6.72 GRAINS PER POUND OF DRY AIR
               SMOKE NUMBER = 39.90
```

Figure 22. Baseline Liner Rig Data at 55% Power.

```
        COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTION TEST - RIG R/U 107, TEST SERIES -A  , READING #  1339
MODEL 250-C20B BASELINE LINER, P/N 6871486, NOZZLE S/N AG2032, JP4 FUEL.
TEST DATE: 06/19/74                               TIME OF DAY: 1254: 0 HOURS

CYCLE POINT  6                                           75% POWER SETTING
************************* EXPERIMENTAL  CONDITIONS ***********************
BURNER AIR FLOW          3.115 LB/SEC     AVG BURNER INLET TEMP   515. DEG F
AVG BURNER INLET PRES   93.3    PSIA      AVG BURNER OUTLET TEMP 1751. DEG F
AVG BURNER DELTA P       7.27   "HG       PRESSURE LOSS             3.72 %
OVERALL F/A RATIO       .01665  (F/M)     FUEL FLOW RATE          211.40 LB/HR
AIR LOAD FACTOR         1.0418            PATTERN FACTOR          .14345
BOT HOT SPOT:  # 40 = 1929.  DEG F        MAX BOT / AVG BOT       1.1013
FUEL INLET TEMPERATURE  86.  DEG F        FUEL INLET PRESSURE     361.4  PSIA
HEAT LOADING PARAMETER  .49103E+07 BTU/HOUR/ATM/CUBIC FOOT (V=  .127315)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1813. 24 1712. 27 1743. 30 1765. 33 1768. 36 1781. 39 1909.
ANNULUS 2 22 1791. 25 1666. 28 1759. 31 1711. 34 1781. 37 1673. 40 1929.
ANNULUS 3 23 1518. 26 1728. 29 1741. 32 1515. 35 1497. 38 1899. 41 1861.

 LEFT SIDE ************* AIR INLET TUBE CONDITIONS ************* RIGHT SIDE
TOTAL PRESSURE           93.32   PSIA    TOTAL PRESSURE          93.33   PSIA
AIR TEMPERATURE          515.  DEG F     AIR TEMPERATURE          516.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE......................  13.95   PSIA

AIR FLOW DATA: P-REF= 117.5 PSIA   DELTA P= 3.98 "HG   T-REF=  87. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       776.     HZ    VOLUMETRIC FLOW RATE  33.76 GAL/HR
FUEL PRESSURE AT F/M  461.1    PSIA     FUEL TEMP AT F/M          85.  DEG F
--------------------------------------------------------------------------
                         SKIN TEMPERATURE SURVEY:
#44=  750. DEG F  #45= 1024. DEG F  #46= 1315. DEG F  #47= 1298. DEG F
#48= 1306. DEG F  #
--------------------------------------------------------------------------
     GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .019044    COMBUSTION EFFICIENCY:  99.7996 %
 MEASURED CO2: 4.001 %   MEASURED O2: 17.50 %   CALCULATED O2: 15.41 %
ANALYSIS CHECK: F/A IS  .017354 WHEN CALCULATED USING MEASURED O2 VALUE
    -----------------------------------------------------------------
                     EMISSIONS MEASUREMENTS
           CONCENTRATION  EMISSIONS INDEX       INSTRUMENT
               PPM        LB/1000 LB FUEL         SOURCE
    -----------------------------------------------------------------
     CO     148.79            7.775            BECKMAN NDIR
     CHX      1.98             .163            BECKMAN  FID
    -----------------------------------------------------------------
     NO      59.57            5.113        AMI  CHEMILUMINESCENCE
     NOX     73.48            6.307        AMI  CHEMILUMINESCENCE
    -----------------------------------------------------------------
     NO      60.20            5.167            BECKMAN NDIR
     NOX     69.93            6.002        BECKMAN  [NDIR + NDUV]
    -----------------------------------------------------------------
       ABSOLUTE HUMIDITY = 15.29 GRAINS PER POUND OF DRY AIR
             SMOKE NUMBER = 42.34
```

Figure 23. Baseline Liner Rig Data at 75% Power.

```
        COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/D 107, TEST SERIES -A  , READING #  1340
MODEL 250-C20B BASELINE LINER, P/N 6871486, NOZZLE S/N AG2032. JP4 FUEL.
TEST DATE: 06/19/74                          TIME OF DAY: 1313:31 HOURS

CYCLE POINT  7                                       100% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW        3.313 LB/SEC     AVG BURNER INLET TEMP   569. DEG F
AVG BURNER INLET PRES 105.2   PSIA      AVG BURNER OUTLET TEMP 1998. DEG F
AVG BURNER DELTA P      8.16   "HG      PRESSURE LOSS            3.81 %
OVERALL F/A RATIO     .02196  (F/M)     FUEL FLOW RATE         261.96 LB/HR
AIR LOAD FACTOR       1.0101            PATTERN FACTOR          .14773
BOT HOT SPOT:  # 40 = 2209.   DEG F     MAX BOT / AVG BOT       1.1057
FUEL INLET TEMPERATURE  92.   DEG F     FUEL INLET PRESSURE     448.7  PSIA
HEAT LOADING PARAMETER  .53873E+07 BTU/HOUR/ATM/CUBIC FOOT (V=  .127315)

******************* BURNER OUTLET TEMPERATURE SURVEY *******************
            ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 2023. 24 1977. 27 2028. 30 2009. 33 1980. 36 1946. 39 2179.
ANNULUS 2 22 1996. 25 1944. 28 2036. 31 1932. 34 2003. 37 2131. 40 2209.
ANNULUS 3 23 1815. 26 1971. 29 2035. 32 1717. 35 1740. 38 2177. 41 2111.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE        105.20   PSIA    TOTAL PRESSURE        105.23   PSIA
AIR TEMPERATURE        569.    DEG F   AIR TEMPERATURE        569.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.....................  13.68    PSIA

AIR FLOW DATA: P-REF= 117.3 PSIA   DELTA P= 4.54 "HG    T-REF=  89. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY      965.      HZ    VOLUMETRIC FLOW RATE  41.93 GAL/HR
FUEL PRESSURE AT F/M  628.7    PSIA     FUEL TEMP AT F/M        89.  DEG F
--------------------------------------------------------------------------
                         SKIN TEMPERATURE SURVEY:
 #44=  854. DEG F   #45= 1166. DEG F   #46= 1505. DEG F   #47= 1455. DEG F
 #48= 1443. DEG F   #
--------------------------------------------------------------------------
            GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .022316     COMBUSTION EFFICIENCY:  99.9321 %
  MEASURED CO2: 4.719 %   MEASURED O2: 16.70 %   CALCULATED O2: 14.42 %
ANALYSIS CHECK: F/A IS  .020179 WHEN CALCULATED USING MEASURED O2 VALUE
      ----------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
          CONCENTRATION  EMISSIONS INDEX         INSTRUMENT
               PPM        LB/1000 LB FUEL          SOURCE
      ----------------------------------------------------------------
       CO     32.27            1.452            BECKMAN NDIR
       CHX     2.09             .148            BECKMAN  FID
      ----------------------------------------------------------------
       NO     99.93            7.385        AMI  CHEMILUMINESCENCE
       NOX   102.40            7.568        AMI  CHEMILUMINESCENCE
      ----------------------------------------------------------------
       NO     90.33            6.676            BECKMAN NDIR
       NOX    95.54            7.061        BECKMAN  [NDIR + NDUV]
      ----------------------------------------------------------------
          ABSOLUTE HUMIDITY = 15.73 GRAINS PER POUND OF DRY AIR
               SMOKE NUMBER = 39.91
```

Figure 24. Baseline Liner Rig Data at 100% Power.

TABLE 7. COMBUSTION SYSTEM PERFORMANCE AT MODEL 250-C20B ENGINE CONDITIONS FOR THE PRODUCTION BASELINE COMBUSTOR (FINAL RIG TEST)

	Idle		Percent Power				
	Grd.	Opr'l.	25	40	55	75	100
A. Emissions							
CO (ppm)		1081.4	786.1	587.4	382.9	148.3	32.3
C_3H_8 (ppm)		174.3	76.3	25.8	8.3	2.0	2.1
NO_x (ppm NO_2)		22.3	32.6	38.5	53.7	69.9	95.5
Smoke Number		11.1	20.8	27.0	39.9	42.3	39.9
CO_2 (%)		2.45	3.03	3.31	3.42	4.00	4.72
B. Gas Analysis							
Comb. Eff. (%)		97.41	98.58	99.11	99.44	99.80	99.93
$F\text{-}A_{chem}/F\text{-}A_{mech}$		1.071	1.080	1.064	1.034	1.010	1.016
C. System Performance							
Pressure Drop (%)		4.32	4.26	4.23	4.18	3.72	3.81
T_{max}/T_{avg} (°F/°F)		1.134	1.137	1.130	1.140	1.101	1.106
Pattern Factor		.1860	.1910	.1840	.2010	.1434	.1477

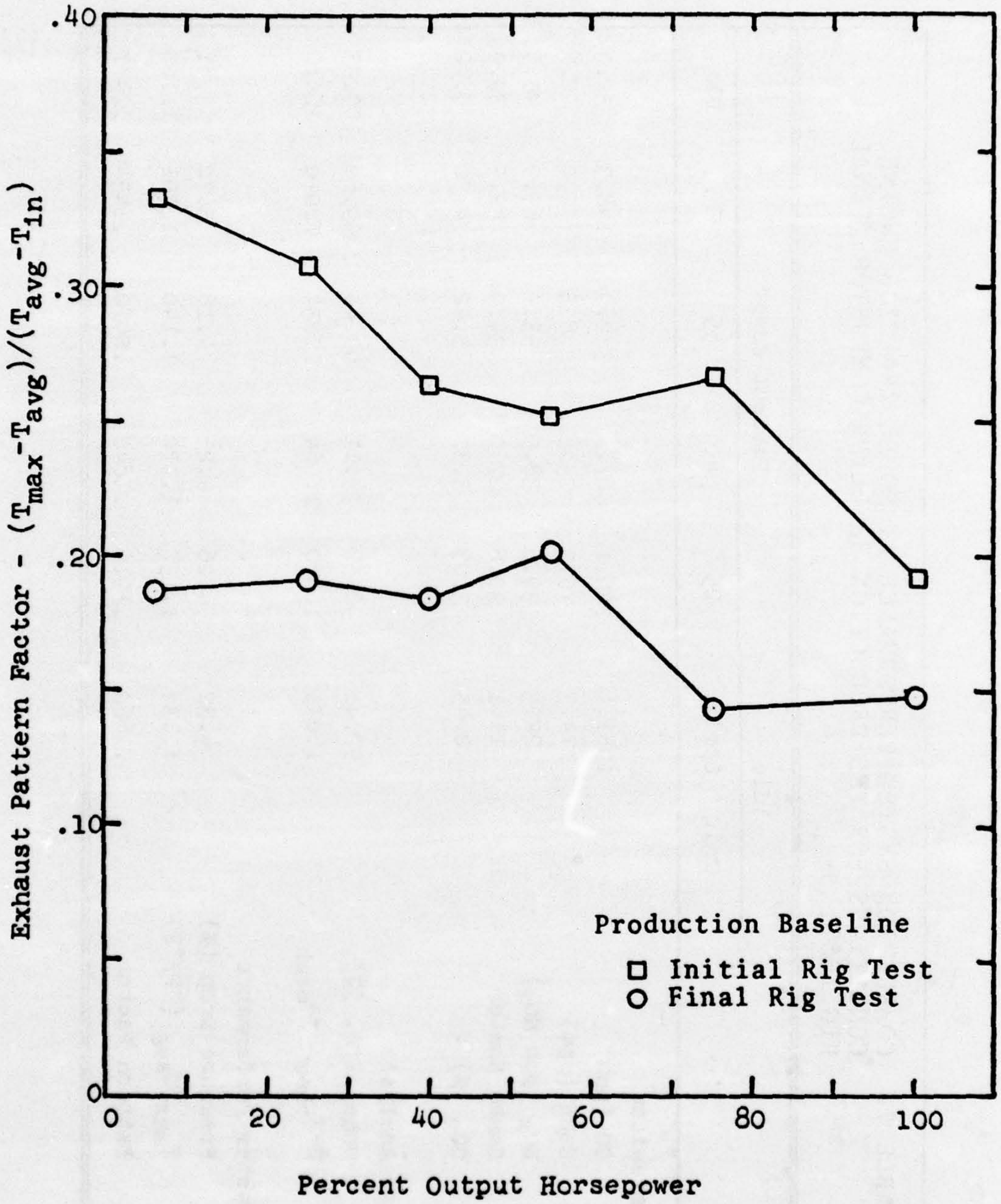

Figure 25. Baseline Liner Exhaust Pattern Factor Comparison.

```
PRODUCTION BASELINE COMBUSTOR RIG TEST (REPEAT) AT 100% POWER CONDITIONS
TEST DATE = 6-18-74        READING NUMBER = 1340              INLET TEMP = 569.
ENGINE      NUMBER/NAME = COMB. RIG  / MODEL 250-C20B          ENGINE TOT = 1490.
OUTER CASE NUMBER/NAME =   6870992 / PRODUCTION BASELINE
LINER       NUMBER/NAME =   6871486 / PRODUCTION BASELINE
```

	* * * * * A N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	2020.3	2035.9	1938.0	1998.0
MAXIMUM TEMPERATURE	2179.0	2209.0	2177.0	2209.0
(AVG-INLET) TEMP	1451.3	1466.9	1369.0	1429.0
(MAX-AVG) TEMP	158.7	173.1	239.0	211.0
MAX TEMP/AVG TEMP	1.0786	1.0850	1.1233	1.1056
(MAX-AVG)/(AVG-IN)	0.1094	0.1180	0.1746	0.1476
(AVG-AVG TOTAL)	22.2	37.8	-60.0	
(TIP-HUB) AVG TEMP				-82.3
(AVG TOTAL-TOT)				508.0

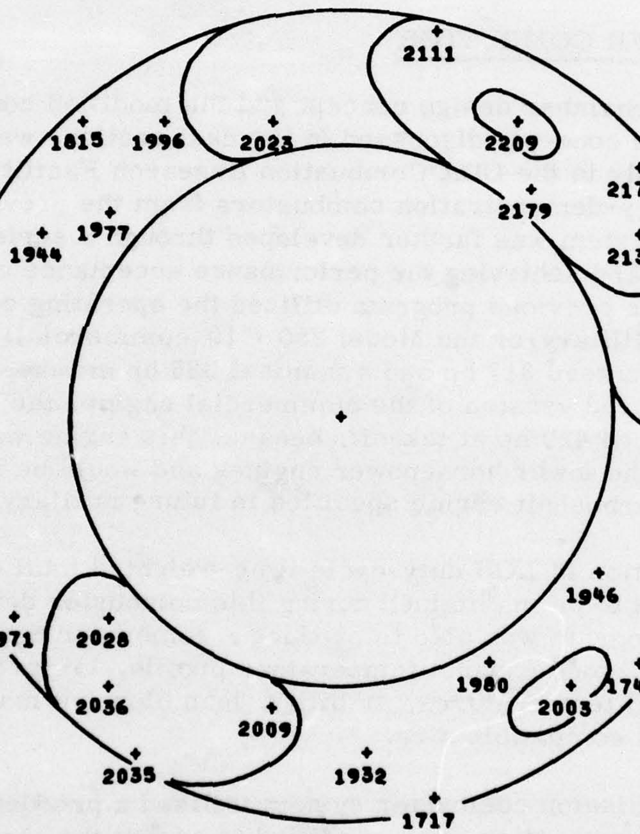

Figure 26. Baseline Liner Exhaust Temperatures at 100% Power, Repeat Test.

Plots of the final baseline combustor exhaust emissions data are given in Figures 27 through 30. Converting these data to emission index values and time-weight averaging them over the LOH duty cycle result in the cycle emissions shown in the top portion of Table 8. Over the duty cycle, the total exhaust emissions (CO, CH_x, NO_x) were 31.639 gm of emissions per kg of fuel. The exhaust emissions for the liner as tested in the previous program at T63-A-5A engine conditions are shown in the lower portion of Table 8.[2] The time-weight-averaged emission index total over the LOH were very similar for each set of engine conditions.

There was no thermal paint run made subsequent to the repair of the combustor. However, liner metal temperatures were recorded and appear in Figure 31.

PRECHAMBER COMBUSTOR

Both the prechamber design concept and the modified conventional combustor design concept, discussed in the next section, were developed simultaneously in the DDA Combustion Research Facility. Beginning with the technology-demonstration combustors from the previous contract, each combustor system was further developed through a series of combustor rig tests toward achieving the performance acceptance criteria defined in Table 2. The previous program utilized the operating conditions of the T63-A-5A (Military) or the Model 250-C19 (commercial) engine, which produced a guaranteed 317 hp and a nominal 335 hp at take-off. This program used the uprated version of the commercial engine, the Model 250-C20B, which produced 420 hp at takeoff, because this engine was replacing the majority of the lower horsepower engines and would be more representative of the turboshaft engine specified in future military aircraft.

A 50% reduction in LOH duty-cycle time-weighted total emissions was the primary goal to be maintained during this combustor development. However, the program was also to produce a combustor that would be engine worthy: i.e., good exhaust temperature profile, low pressure drop, satisfactory metal temperatures, stability, lean blow out margin, acceptable ignition, and compatible size.

Each low-emission combustor system utilized a production Model 250-C20B outer combustion case, modified to accept the changes required for each particular liner. For the prechamber combustor, the outer-case dome was removed and a three-inch cylindrical section added to lengthen the overall case length by three inches. The flow distribution basket was removed and a new one installed having significantly more throughput area to reduce the liner's dependence on the basket hole pattern. External and internal photographs of the prechamber outer case are shown in Figures 32 and 33.

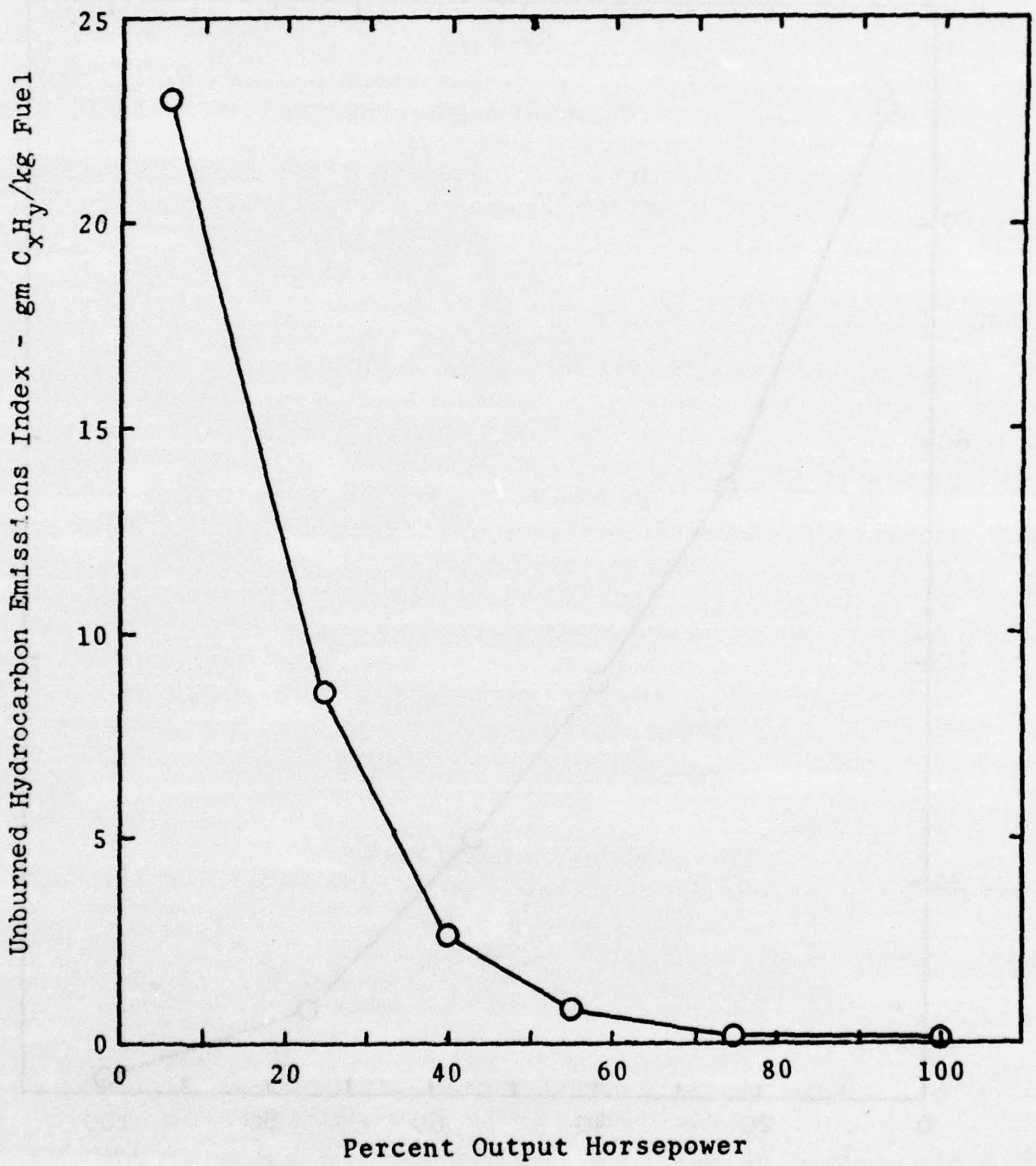

Figure 27. Unburned Hydrocarbon Emissions Found With Baseline Liner.

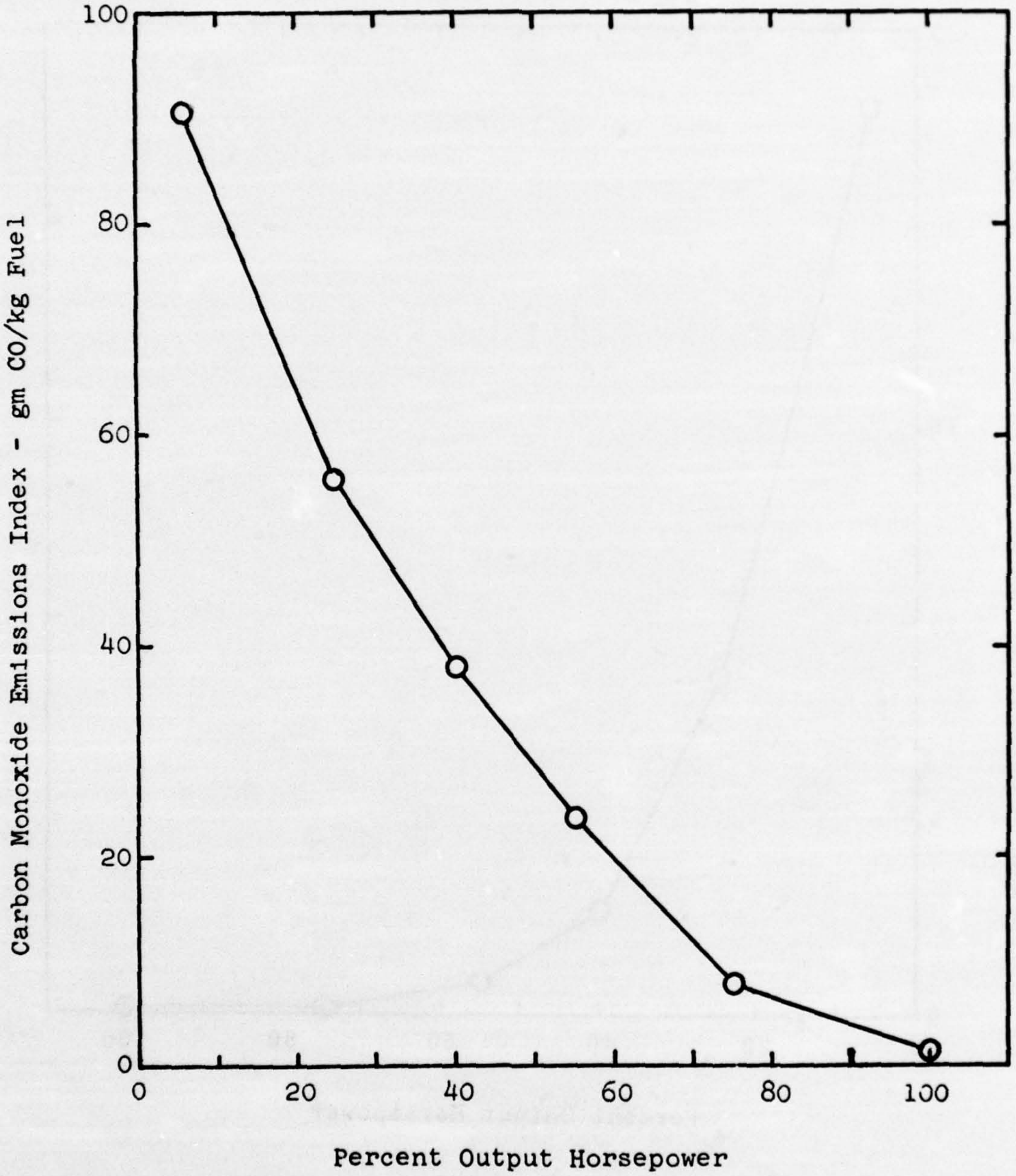

Figure 28. Carbon Monoxide Emissions Found with Baseline Liner.

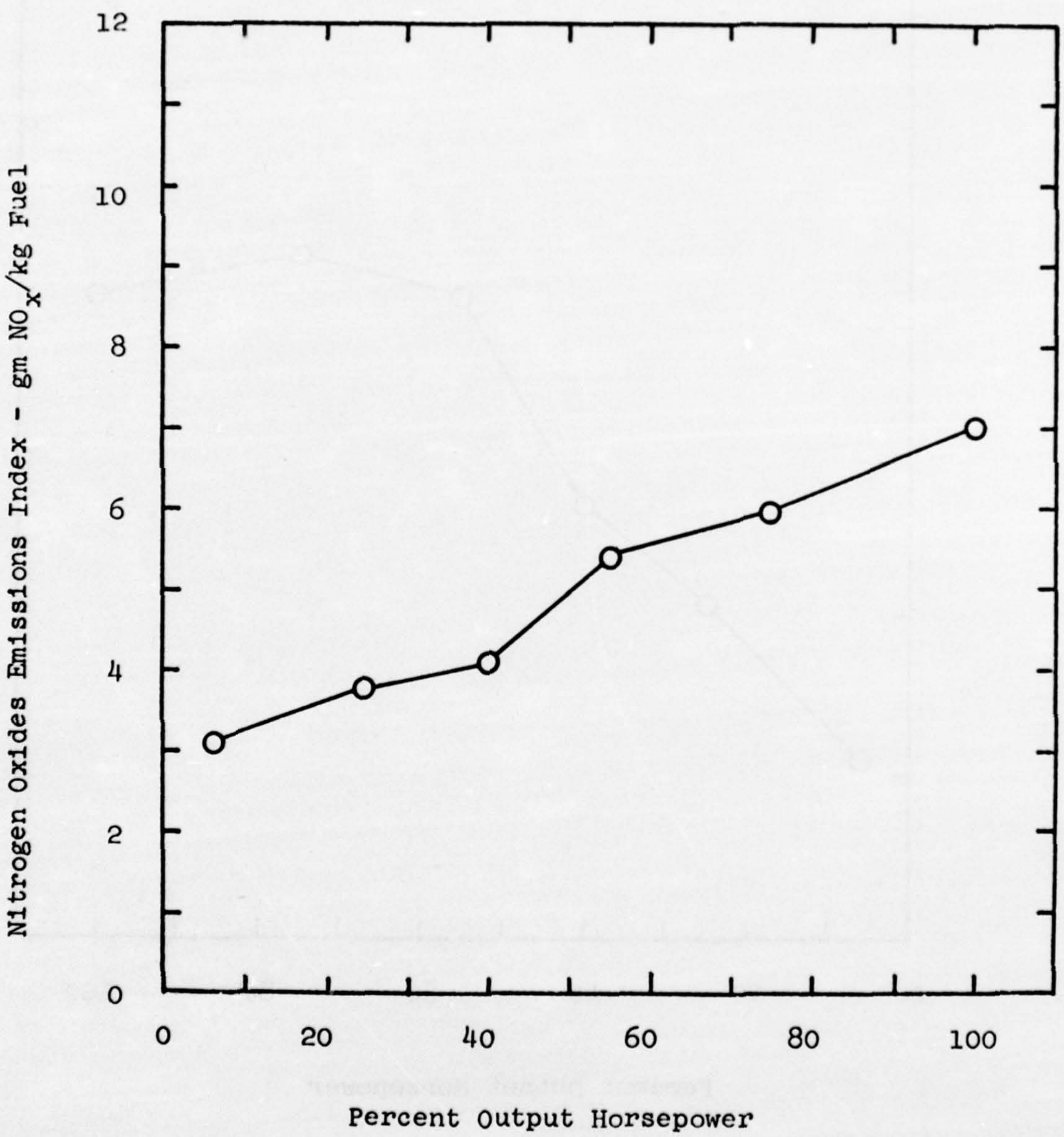

Figure 29. Nitrogen Oxide Emissions Found with Baseline Liner.

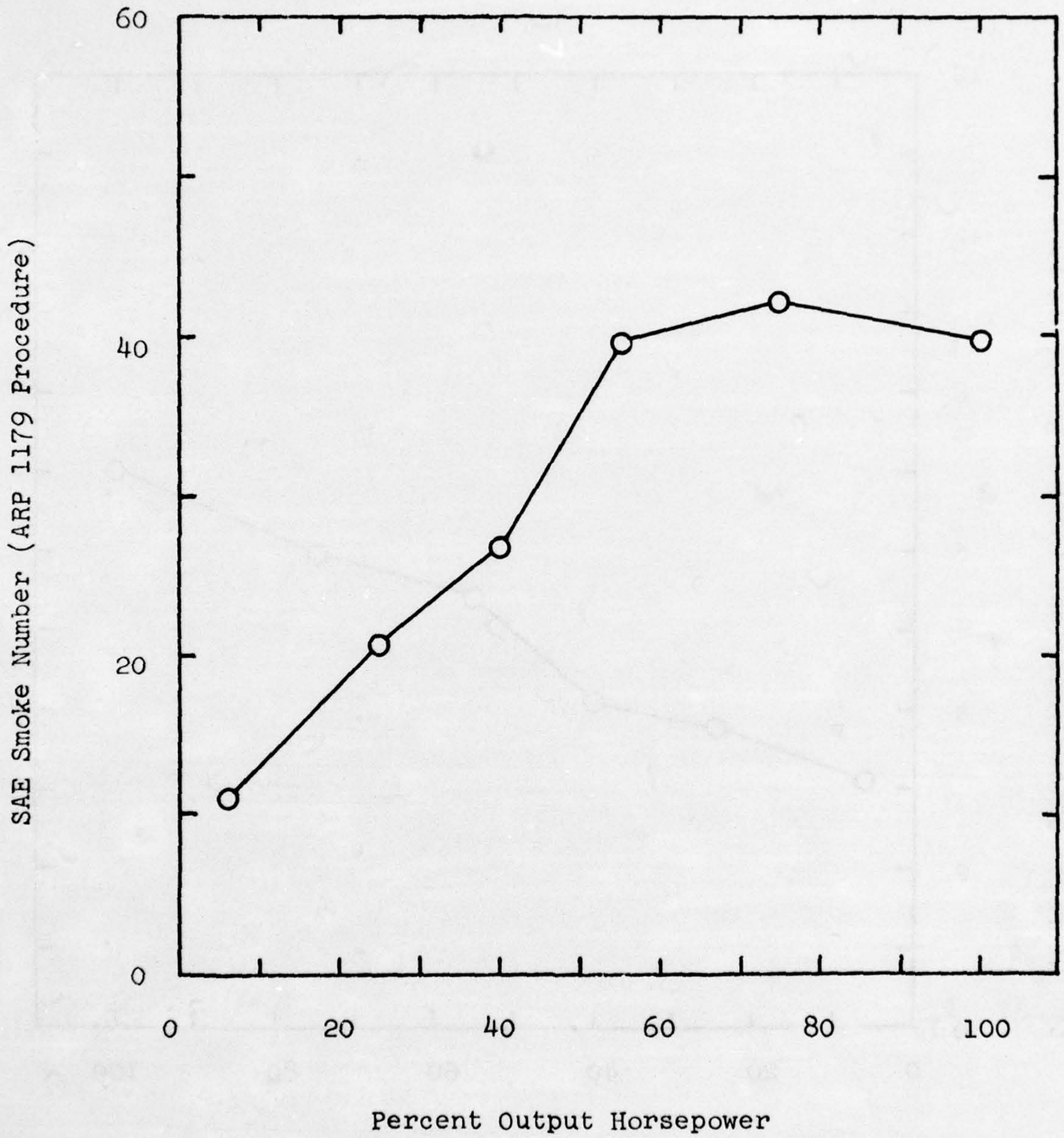

Figure 30. Smoke Number Data Found with Baseline Liner.

TABLE 8. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR BASELINE LINERS.

PRODUCTION MODEL 250-C20B BASELINE COMBUSTOR RIG TEST, JP-4 FUEL TESTED 6-18-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1333.	0.15	70.36	23.062	90.877	3.076	117.015	11.12
1334.	0.00	107.28	8.521	55.784	3.797	68.102	20.80
1335.	0.15	138.17	2.644	38.187	4.114	44.945	27.03
1338.	0.45	163.11	0.805	23.650	5.447	29.902	39.90
1339.	0.20	211.40	0.163	7.775	6.002	13.940	42.34
1340.	0.05	261.96	0.148	1.452	7.061	8.661	39.91
CYCLE TOTALS		160.06	2.287	23.955	5.397	31.639	42.34
PERCENT OF BASELINE		100.00	100.00	100.00	100.00	100.00	

PRODUCTION T63-A-5A BASELINE COMBUSTOR RIG TEST, JP-4 FUEL TESTED 11-9-71

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
54.	0.15	73.17	14.126	80.100	2.505	96.731	3.00
57.	0.00	95.35	4.703	52.603	4.244	61.550	7.00
63.	0.15	118.49	1.864	37.141	5.060	44.065	12.00
69.	0.45	142.41	0.437	25.948	5.076	31.461	17.00
75.	0.20	177.12	0.065	12.716	5.658	18.439	25.00
87.	0.05	229.39	0.047	3.717	6.628	10.392	30.00
CYCLE TOTALS		139.73	1.567	26.446	5.147	33.160	30.00
PERCENT OF BASELINE		87.30	68.53	110.40	95.37	104.81	

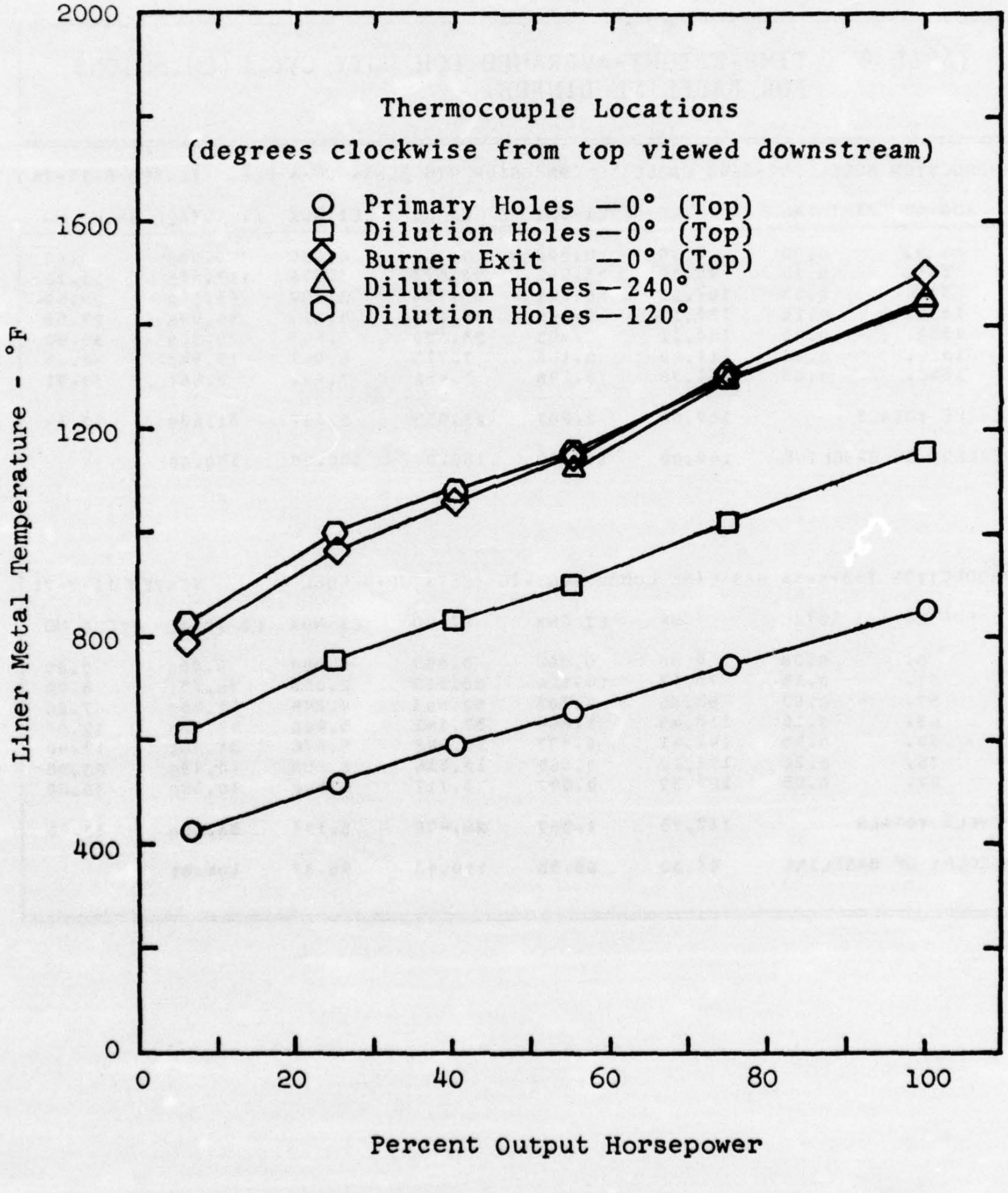

Figure 31. Baseline Liner Metal Temperatures, Repeat Test.

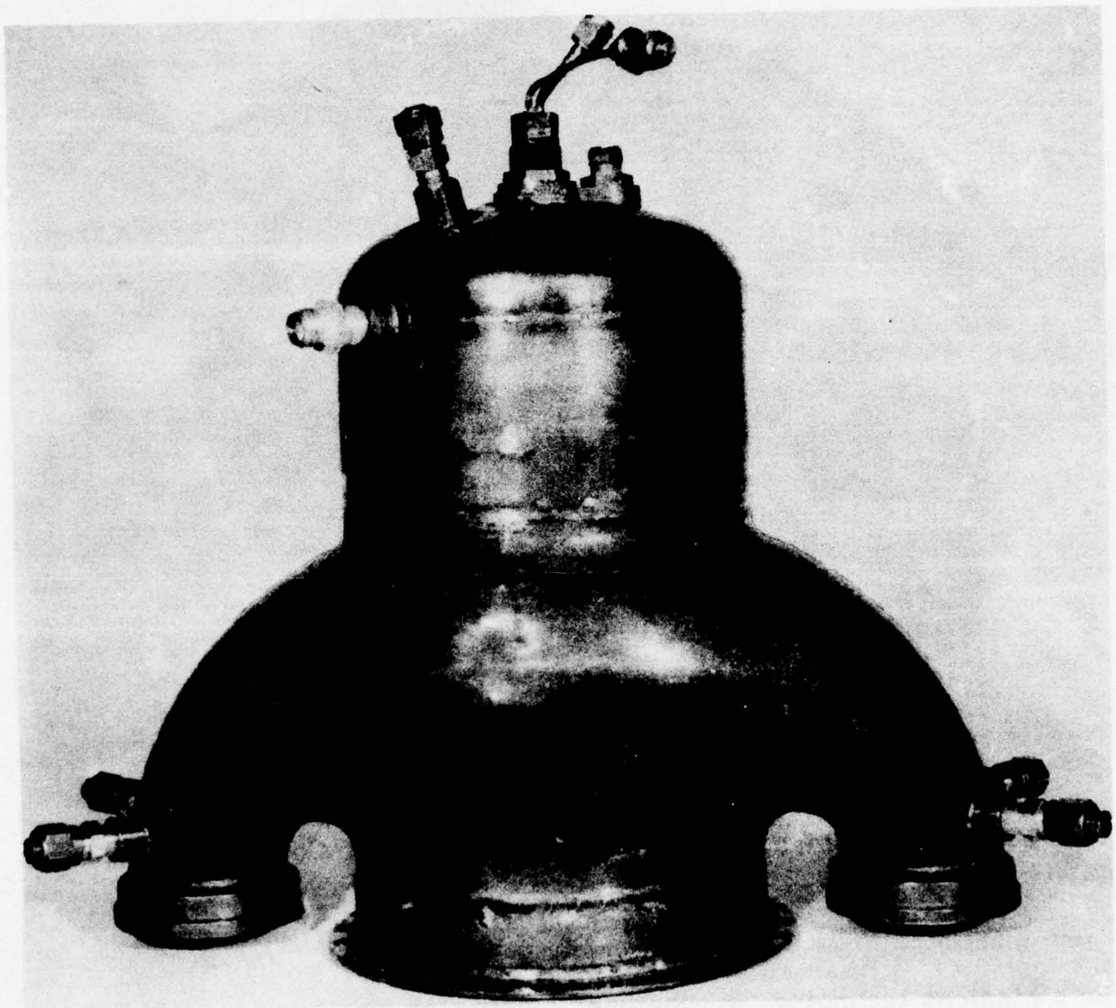

Figure 32. External View of Prechamber Outer Combustion Case.

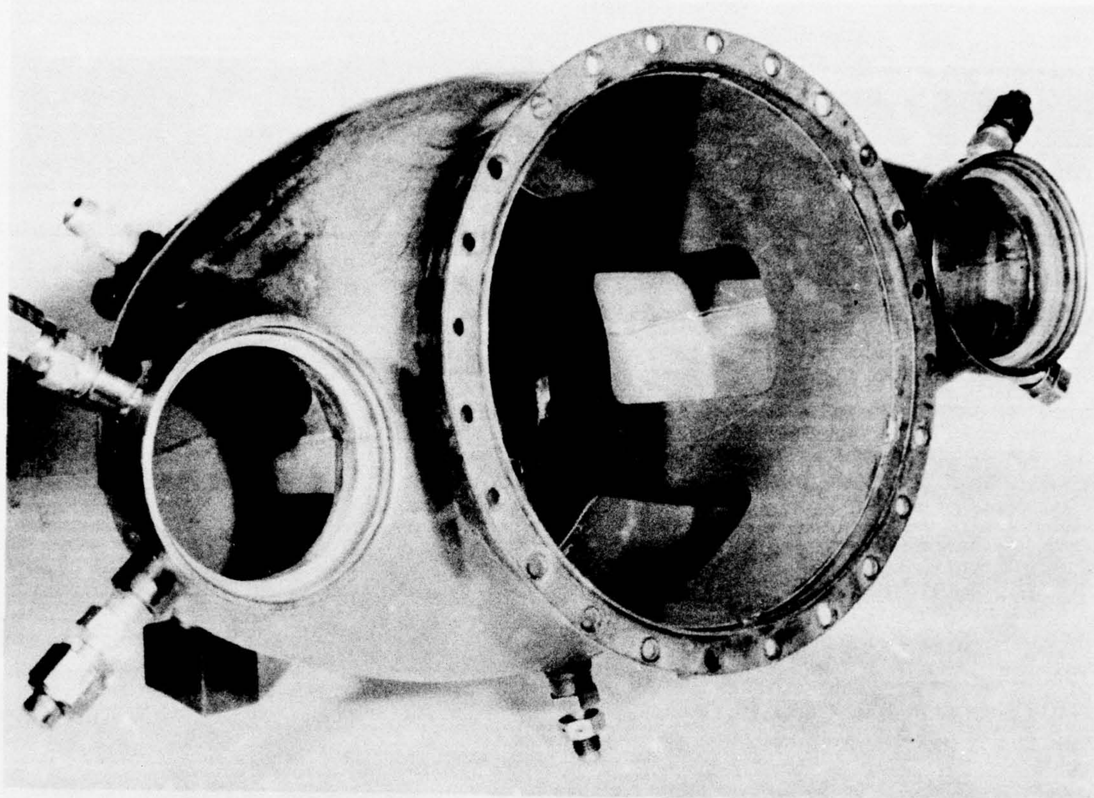

Figure 33. Internal View of Prechamber Outer Combustion Case.

The emissions technology prechamber combustor was operated with two fuel systems: a wall-fuel-film vaporizing system and a center-point, dual-orifice, pressure-atomizing fuel nozzle system (essentially the production fuel nozzle). However, these liners were ignited with a methane-oxygen torch, and thus had no light-off problems. For the combustors developed in this program, standard capacitive-discharge ignition was required, which has been shown from other DDA combustion development programs to be incapable of igniting wall-fuel-film systems at ambient or slightly elevated temperatures. Therefore, for this program only, the centerpoint, pressure atomizing system was considered.

After repair of the combustor rig, it was deemed that, because of the higher thermal loading at the Model 250-C20B conditions, the takeoff performance of the combustors should not be documented unless the performance at lower power conditions was sufficiently good to warrant a check of the 100% power point. Since the emission goals were based on time-weighted steady-state performance, the deletion of the takeoff or 100% power point did not significantly affect the total cycle results because the takeoff point had only a 5% weighting factor. Table 9 shows three sets of baseline rig data: data through 100% power, data only through 75% power (100% hp data deleted), and data through 55% power (75 and 100% hp data deleted).

The percentages of baseline figures for each are based on the entire data set and show the changes in the cycle-averaged emission index as data are removed from the data set. From Table 9 it is clear that deleting the 100% power data produced less than a 10% change in the individual and total emission index cycle totals. The removal of two points or more from the cycle creates significant changes in the emissions cycle totals and could mask any real trends in the data or any estimate in the cycle totals for a full data set.

Each of the prechamber combustors tested during the development phase of the program will be briefly described in this section. The final engine design will be treated more thoroughly, and a set of summary tables will be presented which give pertinent design parameters and performance parameters of interest.

Prechamber Liner No. 1

The technology demonstrator prechamber liner, developed during the previous contract, is shown in Figure 34. This particular version was a wall-fuel-film vaporization liner and could not be operated with the center point fuel nozzle. This liner had a large volume precombustion or prechamber section which was relatively lean, more so than previous experience had shown to be best for center point fuel injection. Thus, the liner was modified to richen the prechamber section and the reaction zone. These changes were made:

1. The bulletnose center body was removed so that a centerpoint fuel nozzle could be used.
2. A portion of the swirler inlet was blocked to richen the prechamber section.
3. A spark plug ferrule was added through the swirler (same location as on baseline liner).

TABLE 9. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS SHOWING SENSITIVITY TO THE ABSENCE AT CYCLE POINT DATA.

PRODUCTION 250-C20B BASELINE COMBUSTOR (DATA THRU 100% HP) RIG TESTED 6-18-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1333.	0.15	70.36	23.062	90.877	3.076	117.015	11.12
1334.	0.00	107.28	8.521	55.784	3.797	68.102	20.80
1335.	0.15	138.17	2.644	38.187	4.114	44.945	27.03
1338.	0.45	163.11	0.805	23.650	5.447	29.902	39.90
1339.	0.20	211.40	0.163	7.775	6.002	13.940	42.34
1340.	0.05	261.96	0.148	1.452	7.061	8.661	39.91
CYCLE TOTALS		160.06	2.287	23.955	5.397	31.639	42.34
PERCENT OF BASELINE		100.00	100.00	100.00	100.00	100.00	

PRODUCTION 250-C20B BASELINE COMBUSTOR (DATA THRU 75% HP) RIG TESTED 6-18-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1333.	0.15	70.36	23.062	90.877	3.076	117.015	11.12
1334.	0.00	107.28	8.521	55.784	3.797	68.102	20.80
1335.	0.15	138.17	2.644	38.187	4.114	44.945	27.03
1338.	0.45	163.11	0.805	23.650	5.447	29.902	39.90
1339.	0.20	211.40	0.163	7.775	6.002	13.940	42.34
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		146.96	2.478	25.961	5.248	33.687	42.34
PERCENT OF BASELINE		91.82	108.34	108.37	97.25	106.47	

PRODUCTION 250-C20B BASELINE COMBUSTOR (DATA THRU 55% HP) RIG TESTED 6-18-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1333.	0.15	70.36	23.062	90.877	3.076	117.015	11.12
1334.	0.00	107.28	8.521	55.784	3.797	68.102	20.80
1335.	0.15	138.17	2.644	38.187	4.114	44.945	27.03
1338.	0.45	163.11	0.805	23.650	5.447	29.902	39.90
0.	0.20	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		104.68	3.413	33.306	4.944	41.663	39.90
PERCENT OF BASELINE		65.40	149.21	139.03	91.61	131.68	

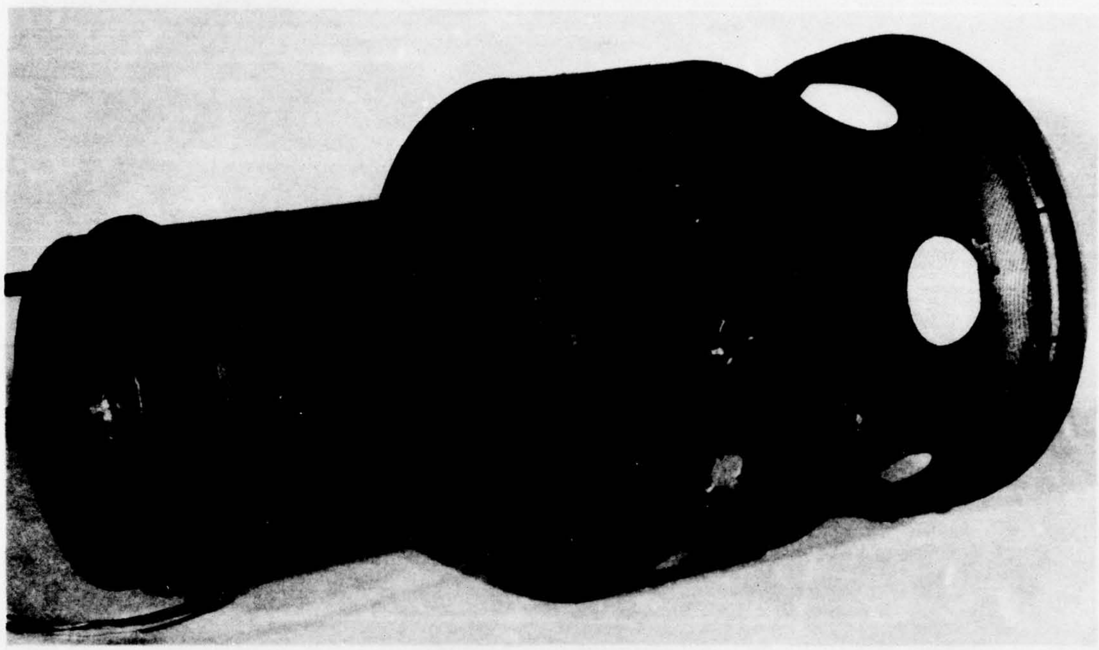

Figure 34. Technology Demonstrator Prechamber Liner.

4. A row of 36 holes was added to promote the mixing of fuel and air before they enter the reaction zone. Each hole was 0.125 in. in diameter and 0.500 in. from the end of the prechamber.
5. The small dilution hole blockage strip was removed to richen the reaction zone.

A photograph of the hardware is shown in Figure 35, as it was tested. The test results for prechamber liner No. 1 are given in Table 10. Emission concentrations except for the unburned hydrocarbons, were quite high. An emissions analysis and a comparison with baseline concentrations are presented in Table 11, which shows that not nearly enough carbon monoxide was consumed and that the liner was extremely smoky.

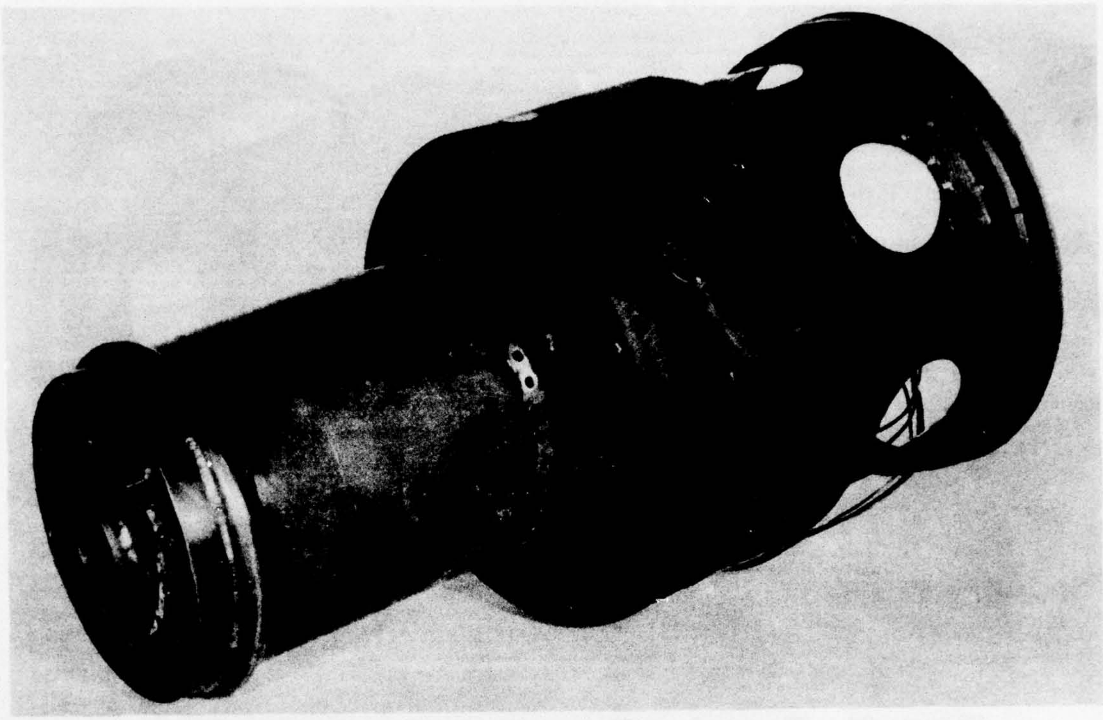

Figure 35. Prechamber Liner No. 1, EX-114014.

Prechamber Liner No. 2

The design objectives that resulted in this prechamber configuration were to increase the prechamber section throughput velocity and to strengthen the reaction zone recirculation. These objectives were sought through the following modifications:

1. The prechamber section was replaced by one of smaller diameter (3.00 inches). This change required relocating the spark plug, resulting in a longer plug, Figure 36, which could pass through the side wall of the prechamber.
2. A radial inflow swirler was added at the exit of the vaporizer tube or prechamber to augment the swirling flow from the axial swirler.
3. The dilution holes were covered slightly to increase the pressure drop and to maintain airflow through the axial swirler at just under 15%.

TABLE 10. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 1 AT MODEL 250-C20B ENGINE CONDITIONS

	Idle	Percent Power				
	Ground Operational	25	40	55	75	100
A. Emissions						
CO (ppm)	556.1	474.3	349.4	309.5	289.6	192.0
C_3H_8 (ppm)	27.0	4.5	1.3	1.0	.9	.9
NO_x (ppm NO_2)	26.9	31.8	40.9	55.0	74.8	100.9
Smoke Number	58.0	80.9	83.3	84.9	--	88.7
CO_2 (%)	2.06	2.45	2.65	2.85	3.26	4.00
B. Gas Analysis						
Comb. Eff. (%)	98.35	99.05	99.36	99.47	99.55	99.74
$F\text{-}A_{chem}/F\text{-}A_{mech}$	.871	.860	.844	.844	.833	.849
C. System Performance						
Pressure Drop (%)	2.46	2.67	2.80	2.90	2.86	2.48
T_{max}/T_{avg} (°F/°F)	1.1617	1.1611	1.1204	1.1332	1.1374	1.1328
Pattern Factor	.2230	.2263	.1707	.1900	.1948	.1856

TABLE 11. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR PRECHAMBER LINER NO. 1.

PRECHAMBER LINER NO. 1, EX-114014, NOZZLE 6874959 RIG 5-1-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1324.	0.15	73.66	3.567	46.665	3.704	53.936	57.95
1325.	0.00	107.53	0.500	33.500	3.689	37.689	80.92
1326.	0.15	137.28	0.134	22.601	4.348	27.083	83.33
1327.	0.45	166.11	0.099	18.674	5.448	24.221	84.87
1328.	0.20	217.85	0.070	15.180	6.440	21.690	0.00
1329.	0.05	262.41	0.062	8.448	7.293	15.803	88.70
CYCLE TOTALS		163.08	0.328	19.310	5.604	25.242	88.70
PERCENT OF BASELINE		101.89	14.32	80.61	103.85	79.78	

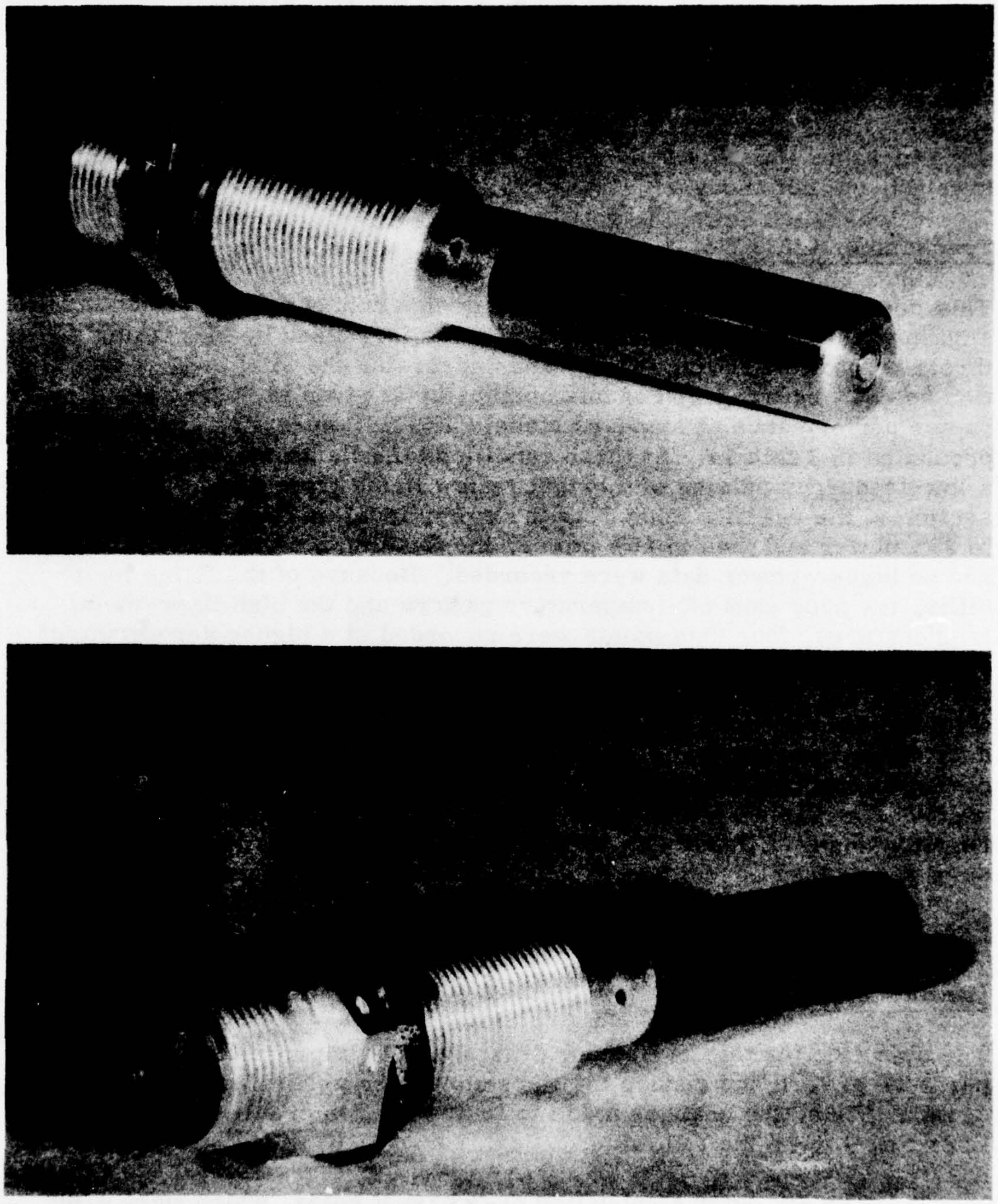

Figure 36. Prechamber Liner Spark Igniter.

A photograph of this prechamber design is shown in Figure 37. A summary of the combustor performance data is presented in Table 12 and shows quite low CO and CH_x levels, but higher than baseline NO_x, and high smoke at high power conditions. Time-weighted LOH duty-cycle emissions are compared with baseline levels through 75% power conditions in Table 13. The table shows that the exhaust emissions were lowered, but not enough.

Prechamber Liner No. 3

This prechamber design continued the design concept of the previous version in which the reaction zone airflow was increased by increasing the throat area of the radial swirler and decreasing the total area of the dilution holes. A photograph of this combustor is given in Figure 38. Combustor performance at standard Model 250-C20B operating conditions is presented in Table 14. At these conditions the flame was unstable, with a low-frequency pulsing of a bright yellow flame from the prechamber section to the reaction zone. As the power level was increased from idle to 25% power and then to 40% power, the flashing became more violent and no higher-power data were recorded. Because of the flame instability, the poor exhaust-temperature pattern and the high liner-metal temperatures, four data points were recorded at a higher aerodynamic loading to assess the effect of the higher velocities and the greater pressure drop on the combustor's performance. The higher loading was achieved by maintaining inlet airflow, temperature, and fuel flow while decreasing inlet pressure. In this manner, the liner-pressure drop increased approximately 60%, from 2.9% to 4.6%. At this higher loading, recorded in Table 15, the flame became stable and changed to blue in the reaction zone. Exhaust CO increased, NO_x decreased, and CH_x and smoke remained essentially unchanged, as did the exhaust temperature pattern and the liner-metal temperatures. Emission summaries over the LOH duty cycle are shown for both loadings in Table 16.

Prechamber Liner No. 4

The objective for this combustor design was to improve the exhaust temperature pattern and reduce the liner-metal temperatures of the previous design. Thus, the changes made to liner No. 3 to create prechamber liner No. 4 were the following:

1. The six outer combustion case basket holes, which were 4.00 inches long by 2.25 inches wide, were shortened by 2.00 inches to give a larger cylindrical path for improving convection cooling.

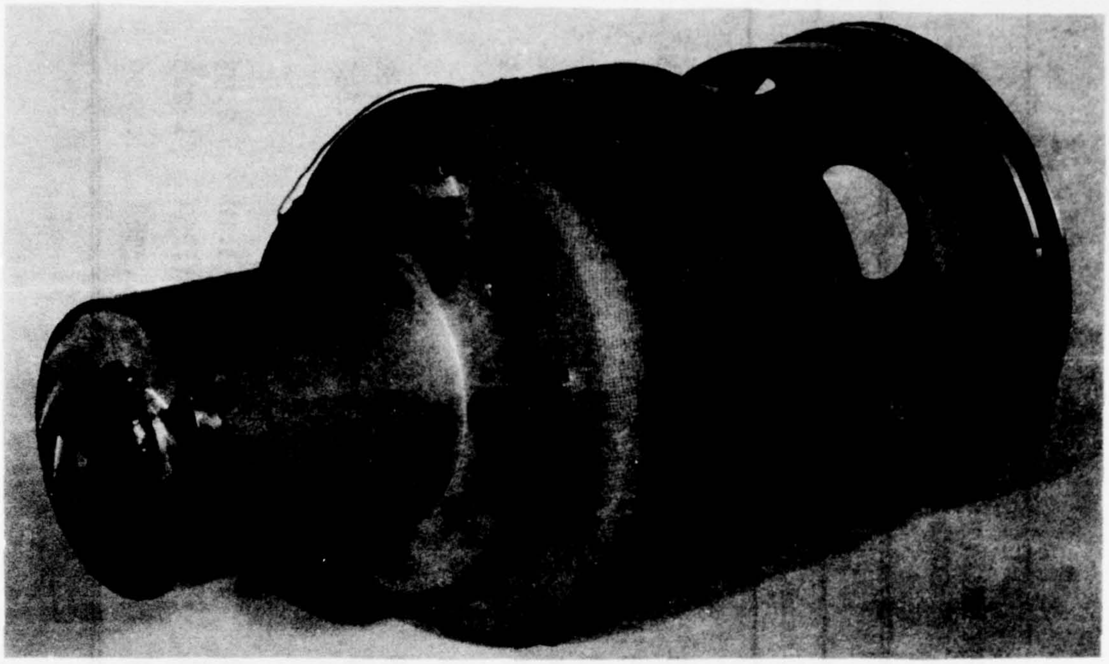

Figure 37. Prechamber Liner No. 2, EX-114016.

2. Thumbnail scoops were added to the downstream edge of each of the six dilution holes to enhance dilution air penetration for improved exhaust temperature profiles.
3. An air dam was added just behind the dilution holes to improve the dilution air feed characteristics and to eliminate dilution air overshoot and turbulence around the back end of the liner.

A photograph of this liner is shown in Figure 39. Initial combustor performance was improved over the previous run, especially the exhaust temperature pattern, but the liner metal temperature behind the air dam overheated at conditions above 55% power, opening the seam behind the dilution holes. The opening of this seam increased the liner metal temperature and worsened the exhaust temperature profile to a point where it was necessary to terminate the test. The data from the run are summarized in Table 17. Emissions were relatively constant through 55% power except for smoke, which increased dramatically. Exhaust emissions are compared with baseline levels over a portion of the LOH duty cycle in Table 18.

TABLE 12. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 2 AT MODEL 250-C20B ENGINE CONDITIONS

	Idle		Percent Power				
	Ground	Operational	25	40	55	75	100
A. Emissions							
CO (ppm)		92.6	150.8	160.7	146.8	119.9	
C_3H_8 (ppm)		1.3	1.2	1.4	1.6	2.1	
NO_x (ppm NO_2)		39.3	60.6	54.4	62.3	80.0	
Smoke Number		1.7	.0	18.0	35.5	52.2	
CO_2 (%)		2.25	2.60	2.85	3.11	3.42	
B. Gas Analysis							
Comb. Eff. (%)		99.78	99.70	99.71	99.75	99.80	
$F\text{-}A_{chem}/F\text{-}A_{mech}$		.919	.905	.927	.900	.856	
C. System Performance							
Pressure Drop (%)		3.22	3.13	3.38	3.12	2.93	
T_{max}/T_{avg} (°F/°F)		1.283	1.275	1.251	1.250	1.213	
Pattern Factor		.3893	.3859	.3580	.3564	.3009	

TABLE 13. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSION FOR PRECHAMBER LINER NO. 2.

PRECHAMBER LINER NO. 2, EX-114016, NOZZLE 6874959 RIG 6-21-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1343.	0.15	70.23	0.174	7.691	5.361	13.226	0.00
1344.	0.00	108.70	0.138	10.720	7.073	17.931	0.02
1345.	0.15	137.20	0.149	10.689	5.944	16.782	18.02
1346.	0.45	164.18	0.147	8.741	6.089	14.977	35.46
1347.	0.20	214.49	0.169	6.207	6.804	13.180	52.19
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		147.89	0.156	8.202	6.224	14.582	52.19
PERCENT OF BASELINE		100.64	6.28	31.59	118.60	43.29	

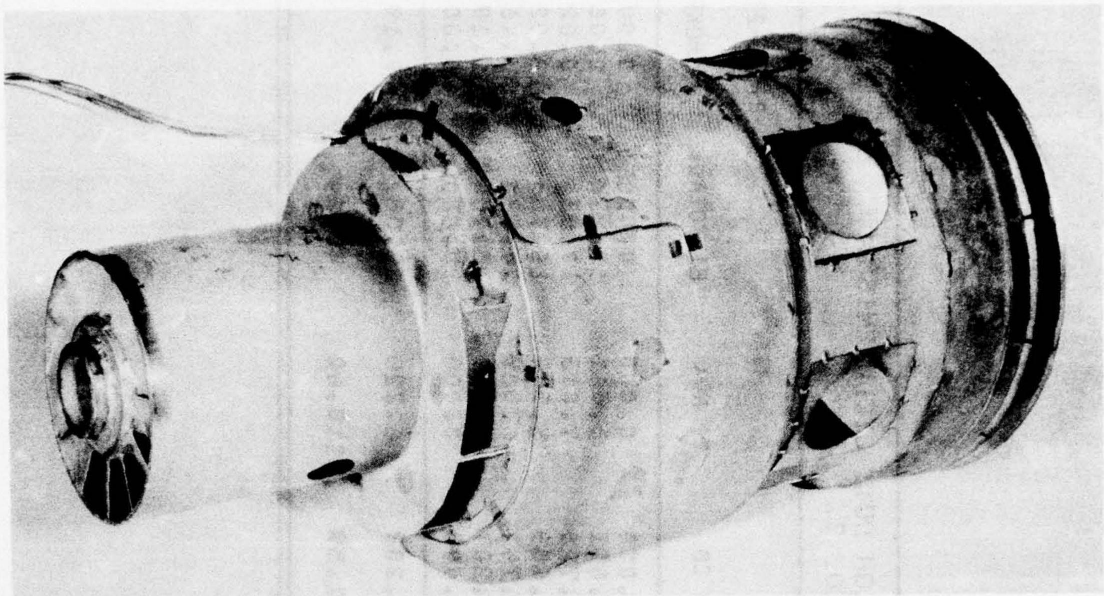

Figure 38. Prechamber Liner No. 3, EX-114016A.

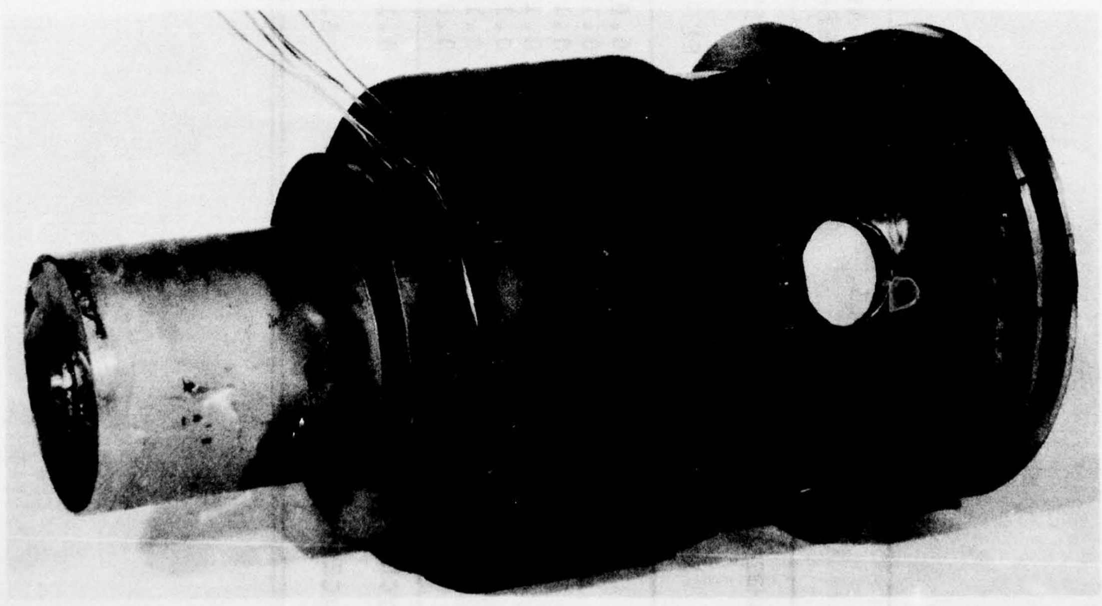

Figure 39. Prechamber Liner No. 4, EX-114771.

TABLE 14. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 3 WITH A STANDARD, DUAL-ORIFICE, PRESSURE-ATOMIZING FUEL NOZZLE AT STANDARD AERODYNAMIC LOADING AT MODEL 250-C20B ENGINE CONDITIONS

	Idle		Percent Power				
	Ground	Operational	25	40	55	75	100
A. Emissions							
CO (ppm)		104.9	116.2	112.4			
C_3H_8 (ppm)		5.1	2.5	2.1			
NO_x (ppm NO_2)		16.8	47.8	60.0			
Smoke Number		.8	1.4	1.9			
CO_2 (%)		2.25	2.55	2.85			
B. Gas Analysis							
Comb. Eff. (%)		99.75	99.76	99.78			
$F\text{-}A_{chem}/F\text{-}A_{mech}$		.931	.889	.917			
C. System Performance							
Pressure Drop (%)		2.72	2.95	2.92			
T_{max}/T_{avg} (°F/°F)		1.303	1.257	1.261			
Pattern Factor		.4158	.3600	.3710			

TABLE 15. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 3 WITH A STANDARD, DUAL-ORIFICE, PRESSURE-ATOMIZING FUEL NOZZLE AT HIGH AERODYNAMIC LOADING AT MODEL 250-C20B ENGINE CONDITIONS

	Idle		Percent Power				
	Ground	Operational	25	40	55	75	100
A. Emissions							
CO (ppm)		175.0		154.7	162.8	170.9	
C_3H_8 (ppm)		6.1		2.6	2.6	2.6	
NO_x (ppm NO_2)		19.4		51.0	63.0	73.0	
Smoke Number		1.0		1.5	1.4	.8	
CO_2 (%)		2.25		2.70	2.95	3.42	
B. Gas Analysis							
Comb. Eff. (%)		99.61		99.70	99.71	99.74	
$F\text{-}A_{chem}/F\text{-}A_{mech}$		.911		.871	.873	.858	
C. System Performance							
Pressure Drop (%)		4.68		4.52	4.68	4.55	
T_{max}/T_{avg} (°F/°F)		1.323		1.251	1.274	1.278	
Pattern Factor		.4425		.3564	.3910	.3953	

TABLE 16. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR PRECHAMBER LINER NO. 3

PRECHAMBER LINER NO. 3, EX-114016A, NOZZLE 6874959, STD. LOADING RIG 7-5-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1400.	0.15	71.42	0.676	8.816	2.319	11.811	0.84
1401.	0.00	107.62	0.276	8.268	5.591	14.135	1.41
1402.	0.15	136.15	0.214	7.411	6.493	14.118	1.94
0.	0.45	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.20	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		31.14	0.373	7.894	5.057	13.324	1.94
PERCENT OF BASELINE		99.54	3.91	14.11	134.36	19.24	

PRECHAMBER LINER NO. 3, EX-114016A, NOZZLE 6874959, HIGH LOADING RIG 7-5-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1399.	0.15	73.63	0.792	14.360	2.613	17.765	0.99
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1403.	0.15	139.80	0.267	10.207	5.528	16.002	1.51
1404.	0.45	162.99	0.245	9.858	6.268	16.371	1.43
1405.	0.20	175.80	0.211	8.847	6.209	15.267	0.76
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		140.52	0.283	10.011	5.856	16.149	1.51
PERCENT OF BASELINE		95.62	11.41	38.56	111.57	47.94	

TABLE 17. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 4 WITH PRODUCTION MODEL 250-C20B FUEL NOZZLE AT MODEL 250-C20B ENGINE CONDITIONS

	Idle		Percent Power				
	Ground	Operational	25	40	55	75	100
A. Emissions							
CO (ppm)		93.5	166.8	162.7	139.0		
C_3H_8 (ppm)		2.1	1.8	1.6	2.0		
NO_x (ppm NO_2)		38.8	51.4	49.2	64.5		
Smoke Number		.0	17.5	38.3	52.2		
CO_2 (%)		2.16	2.55	2.80	2.90		
B. Gas Analysis							
Comb. Eff. (%)		99.77	99.67	99.71	99.74		
$F\text{-}A_{chem}/F\text{-}A_{mech}$		.905	.879	.884	.853		
C. System Performance							
Pressure Drop (%)		2.83	3.00	2.89	2.97		
T_{max}/T_{avg} (°F/°F)		1.195	1.195	1.167	1.213		
Pattern Factor		.2655	.2697	.2348	.3029		

TABLE 18. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR PRECHAMBER LINER NO. 4

PRECHAMBER LINER NO. 4, EX-114771, NOZZLE 6874959 RIG 8-6-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1442.	0.15	71.71	0.289	7.991	5.452	13.732	0.00
1443.	0.00	107.81	0.204	11.730	5.937	17.871	17.51
1444.	0.15	135.41	0.161	10.507	5.218	15.886	38.34
1445.	0.45	164.48	0.186	8.388	6.395	14.969	52.22
0.	0.20	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		105.08	0.192	8.757	6.071	15.020	52.22
PERCENT OF BASELINE		100.39	5.62	26.29	122.79	36.05	

Prechamber Liner No. 5

The previous three prechamber combustors used massive amounts of swirl air through the vaporizer tube. Temperature profile, stability, and exhaust smoke were erratic from one test to another with no consistent improvement trend. Also, all of the prechamber combustors had operated with high liner-metal temperatures. Therefore, the next prechamber liner incorporated changes specifically directed toward solving these deficiencies.

1. The radial swirler was removed and the vaporizer tube was shortened 0.50 inch to 3.00 inches overall. The side-mounted spark igniter was moved 1.00 inch upstream for improved light-off.
2. A row of twelve 0.360-inch-diameter primary holes were added 1.28 inches downstream of the vaporizer tube exit in the reaction zone.
3. The total of 1.25 inches of axial length removed from the vaporizer tube (0.50 inch) and radial swirler (0.75 inch) were added to the back of the reaction zone.
4. A reverse-flow film cooling annulus was added at the back of the reaction zone to cool the cylindrical section of that portion of the liner.
5. Two of the six 1.300-inch-diameter dilution holes were closed, and the remaining four, one 30° above and one 30° below horizontal on each side of the liner, were increased to 1.500 inches in diameter with individual, external aft air dams and internal aft thumbnail scoops.
6. Also, a row of 72 film cooling holes of 0.062 inch in diameter each were added downstream of the dilution holes to cool the ex haust metal and rear seal area of the liner.
7. The fuel nozzle was also changed from the baseline production, dual-orifice, pressure atomizing injector to the separately controlled pilot, airblast main fuel injector, EX-114779, see Figure 40.

A photograph of prechamber liner No. 5 is shown in Figure 41. The initial data point for this liner was operational idle at standard Model 250-C20B conditions with no pilot fuel nozzle fuel flow. These data are shown in Table 19. All emissions were high, so the fuel nozzle flows were adjusted until the pilot was flowing at approximately 40 lb/hr and the main airblast fuel system was flowing the balance, or 30 lb/hr. For this condition, CO, CH_x, and smoke increased, and NO_x concentrations decreased. The same idle condition was run at a higher aerodynamic loading (increased air mass flow) and a 5.0 lb/hr pilot fuel flow. As seen in Table 20, CO, CH_x, and

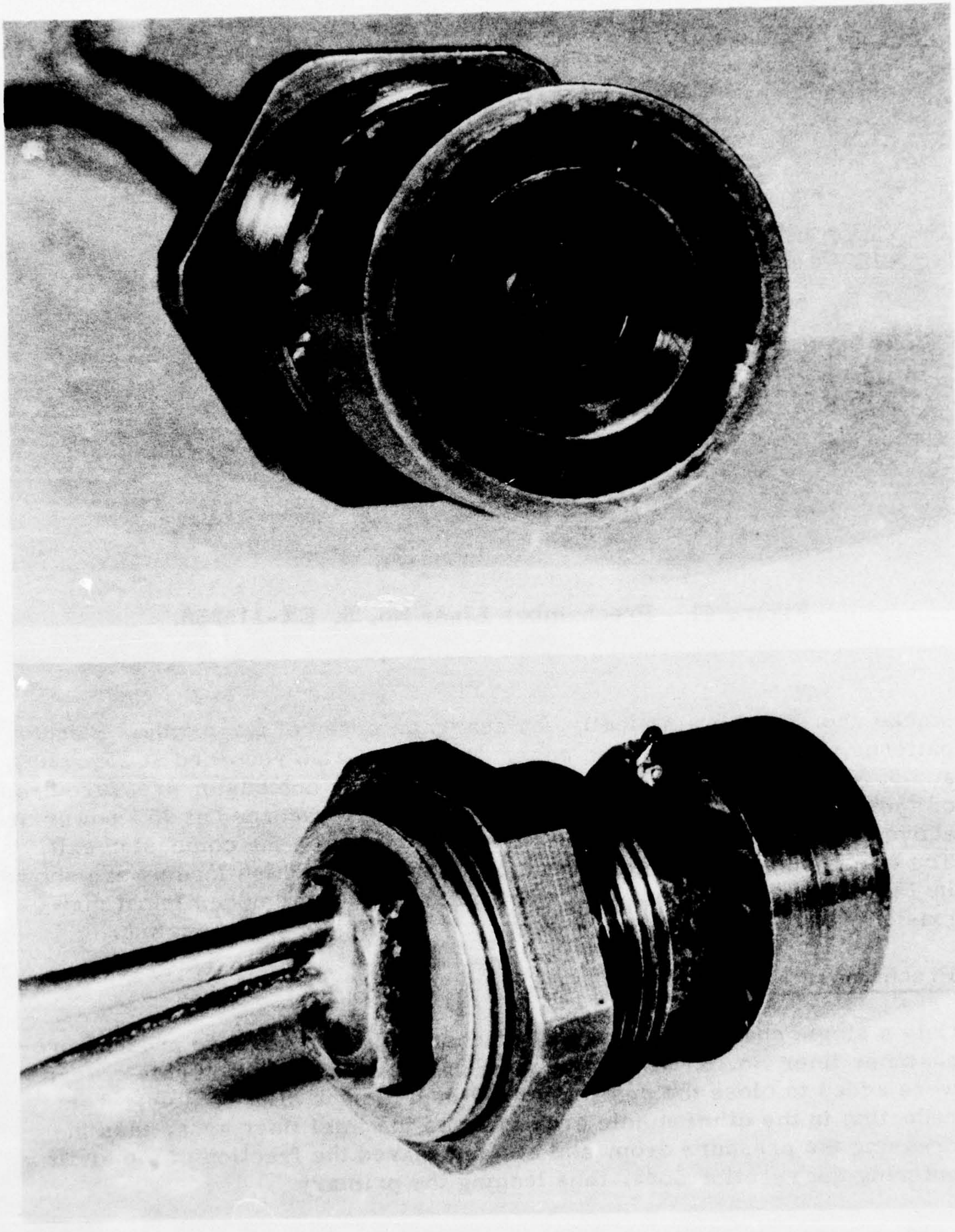

Figure 40. Airblast Fuel Nozzle, EX-114779, with Screen Impingement, Controlled Pilot.

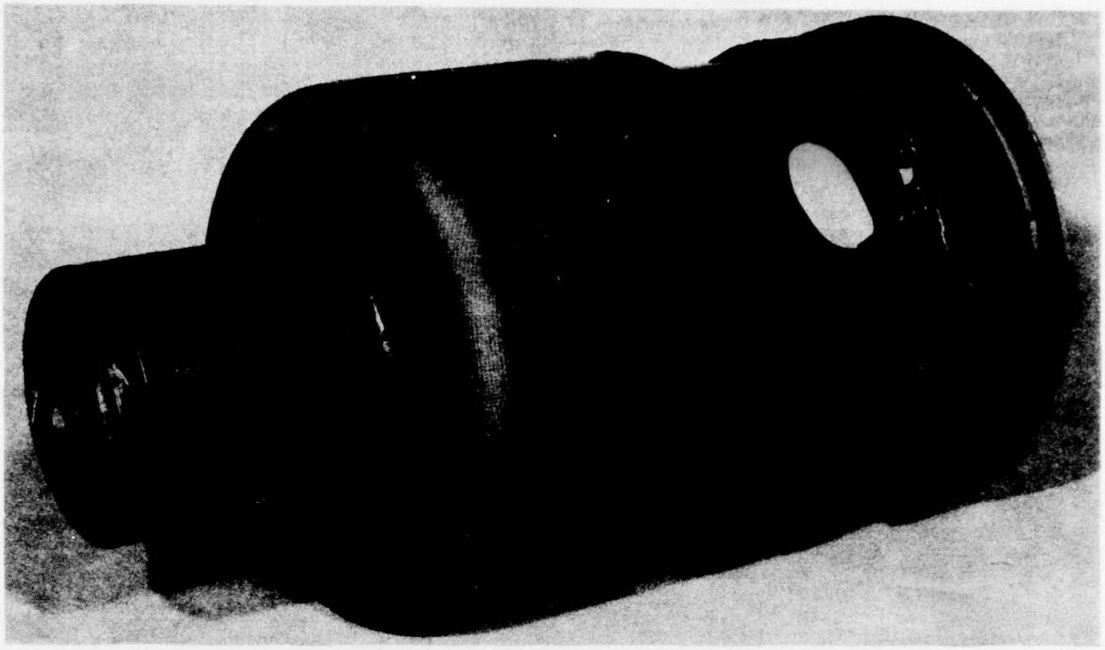

Figure 41. Prechamber Liner No. 5, EX-115256.

smoke decreased dramatically, by nearly an order of magnitude. Exhaust patterns, however, remained poor. Data were also recorded at 25%, 40%, and 55% power at the high loading that indicated a combustor pressure drop of approximately 3.8%. No emissions data were recorded at 75% power or above because of the high temperatures measured in the combustor exit. The emission index values through 55% power at the high loading are shown in Table 21. Both CO and CH_x were quite low, with smoke almost non-existent, but NO_x emissions were nearly 50% higher than baseline.

Prechamber Liner No. 6

Only a single change was made to prechamber liner No. 5 to produce prechamber liner No. 6. As can be seen in Figure 42, dilution hole covers were added to close the upstream 0.50 inch of each dilution hole. This reduction in the dilution hole area lowered the total liner area, thus increasing the pressure drop, and also increased the fraction of the airflow entering the reaction zone, thus leaning the primary.

TABLE 19. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 5 AT STANDARD LOADING WITH DDA AIRBLAST FUEL NOZZLE EX-114779 AND AT MODEL 250-C20B ENGINE CONDITIONS

Operating Condition	Operational Idle		75% Power
Pilot Flow (lb/hr)	.0	40.6	5.0
A. Emissions			
CO (ppm)	651.5	1042.5	--
C_3H_8 (ppm)	87.2	225.1	--
NO_x (ppm NO_2)	33.4	24.8	--
Smoke Number	7.0	31.0	--
CO_2 (%)	2.50	2.23	--
B. Gas Analysis			
Comb. Eff. (%)	98.49	97.04	--
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.064	.978	--
C. System Performance			
Pressure Drop (%)	2.49	2.75	2.79
T_{max}/T_{avg} (°F/°F)	1.2523	1.2547	1.2519
Pattern Factor	.3492	.3553	.3552

TABLE 20. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 5 AT HIGH LOADING WITH DDA AIRBLAST FUEL NOZZLE EX-114779 AND AT MODEL 250-C20B ENGINE CONDITIONS

	Idle	Percent Power				
	Ground Operational	25	40	55	75	100
A. Emissions						
CO (ppm)	82.8	75.6	70.4	63.1	--	
C_3H_8 (ppm)	7.2	5.1	4.3	4.1	--	
NO_x (ppm NO_2)	30.3	47.8	63.4	80.2	--	
Smoke Number	1.3	.0	.0	1.9	--	
CO_2 (%)	2.38	2.85	3.08	3.31	--	
B. Gas Analysis						
Comb. Eff. (%)	99.79	99.84	99.85	99.86	--	
$F\text{-}A_{chem}/F\text{-}A_{mech}$	.991	1.001	.987	.968	--	
C. System Performance						
Pressure Drop (%)	3.72	3.72	3.73	3.93	3.80	
T_{max}/T_{avg} (°F/°F)	1.2390	1.2329	1.1936	1.2534	1.2390	
Pattern Factor	.3294	.3265	.2751	.3605	.3390	

TABLE 21. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR PRECHAMBER LINER NO. 5

PRECHAMBER LINER NO. 5, EX-115256, NOZZLE EX-114779, HIGH LOADING RIG 9-19-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1507.	0.15	83.07	0.958	7.034	4.228	12.220	1.28
1508.	0.00	128.42	0.582	5.438	5.647	11.667	0.02
1509.	0.15	160.40	0.449	4.638	6.852	11.939	0.00
1510.	0.45	196.49	0.392	3.800	7.936	12.128	1.92
0.	0.20	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		124.94	0.459	4.284	7.357	12.101	1.92
PERCENT OF BASELINE		119.36	13.46	12.86	148.81	29.04	

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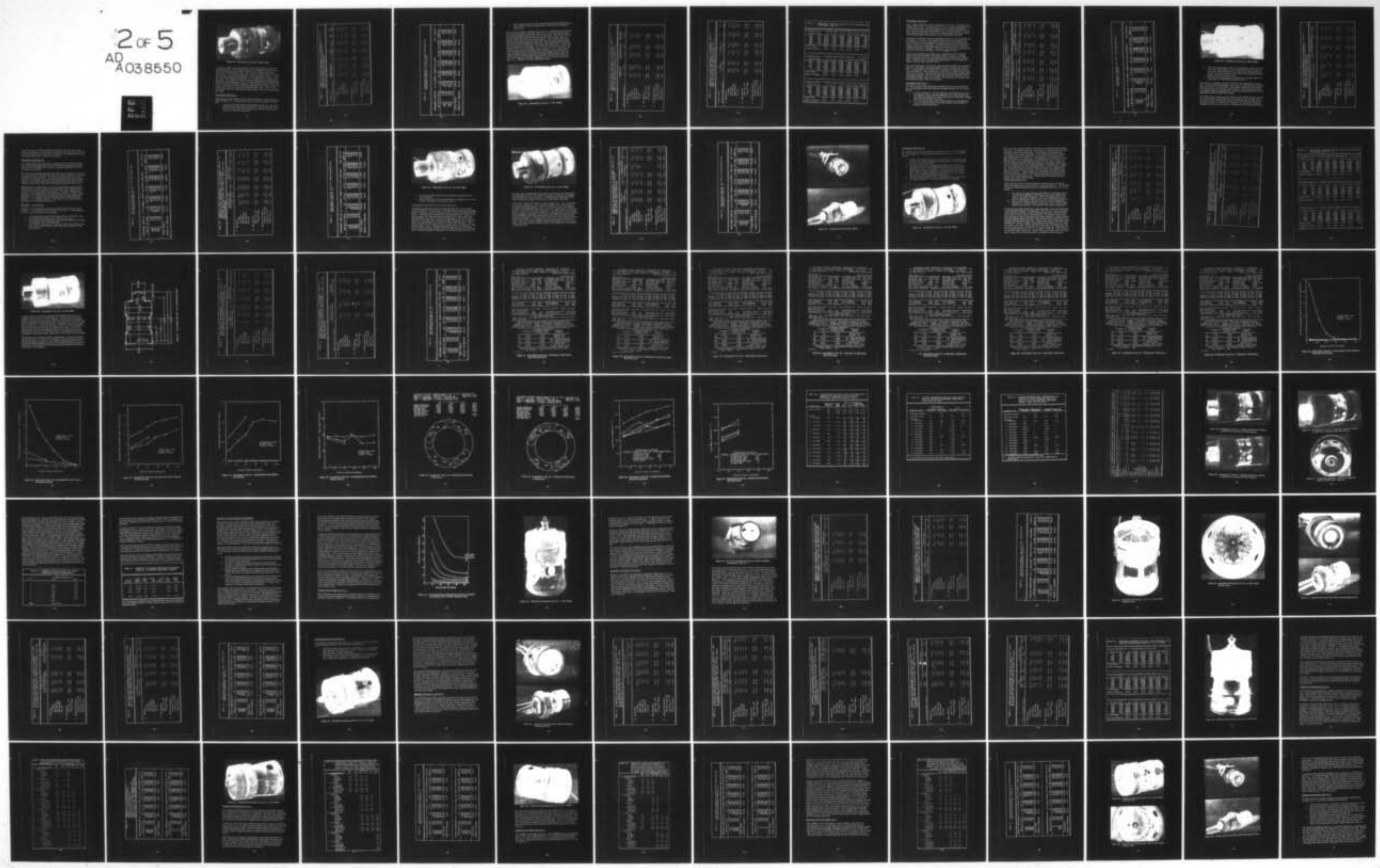

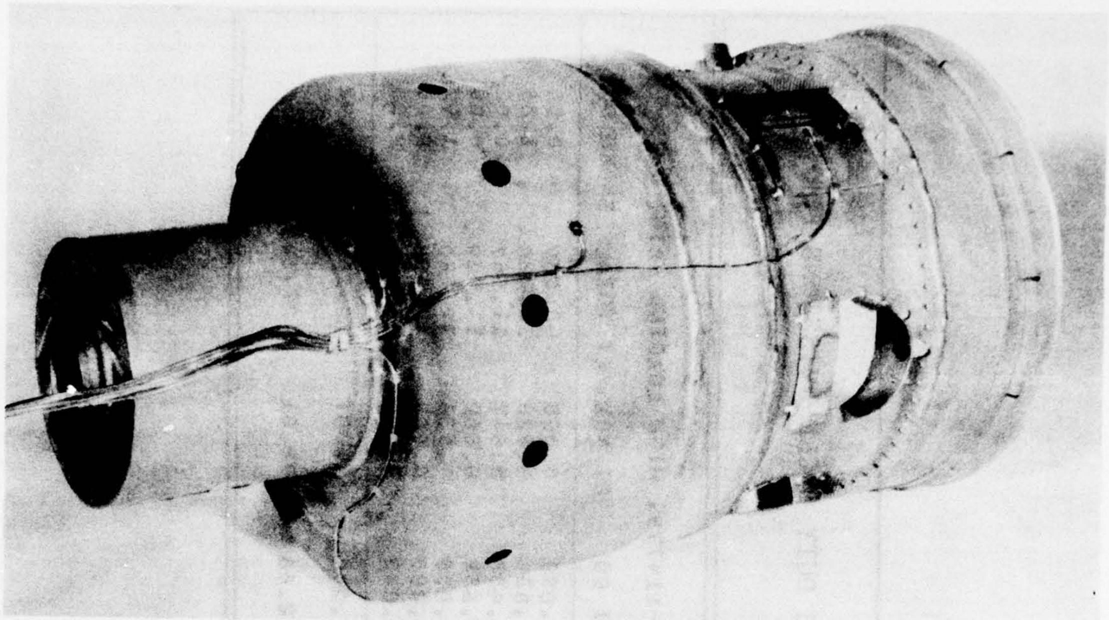

Figure 42. Prechamber Liner No. 6, EX-115861.

A summary of the test data is shown in Table 22 for the four operating conditions tested. Of particular interest is the exhaust emissions sensitivity to varying amounts of pilot fuel flow from airblast fuel nozzle EX-114779. At operational idle, an increase in pilot flow from 10 to 40 lb/hr increased all exhaust emissions, particularly CO and CH_X. A similar trend was exhibited at 25% power. At low pilot flows, exhaust smoke was zero. The exhaust temperature pattern appeared to be improving although not yet satisfactory. Also, the measured liner metal temperatures were below 1300°F through 75% power, thus showing promise of good durability. Constituent and total emission index values are shown in Table 23 for the data recorded at the lowest pilot fuel-flow rates. The CO, CH_X, and smoke levels were well within contract goals, but NO_X emissions were quite high.

<u>Prechamber Liner No. 7</u>

A photograph of the seventh version of the prechamber combustor liner is shown in Figure 43. Changes in this liner from the previous version follow:

1. A set of 12, equally-spaced, intermediate-quench air holes were added downstream of the primary holes. The top two and bottom two holes were .438 inch in diameter and the four holes of each side were .375 inch in diameter.

TABLE 22. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 6 USING DDA AIRBLAST FUEL NOZZLE EX-114779 AT MODEL 250-C20B ENGINE CONDITIONS

Percent Power	Operational Idle		25%			55%	75%
Pilot Flow Rate (lb/sec)	10.0	40.1	.0	5.0	10.1	5.4	4.2
A. Emissions							
CO (ppm)	181.3	1160.8	99.1	118.0	587.4	48.1	30.2
C_3H_8 (ppm)	19.5	246.1	6.1	5.1	33.0	4.5	4.1
NO_x (ppm NO_2)	23.7	30.1	54.4	54.4	42.9	89.3	145.4
Smoke Number	.0	17.2	.0	--	4.8	.0	.0
CO_2 (%)	2.70	2.45	3.21	3.21	3.11	3.89	4.61
B. Gas Analysis							
Comb. Eff. (%)	99.61	97.02	99.82	99.79	99.03	99.90	99.92
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.104	1.055	1.122	1.127	1.111	1.123	1.168
C. System Performance							
Pressure Drop (%)	4.25	3.96	3.80	4.07	3.96	4.13	4.27
T_{max}/T_{avg} (°F/°F)	1.1733	1.2372	1.2141	1.2278	1.2066	1.1995	1.1974
Pattern Factor	.2349	.3261	.2949	.3138	.2867	.2790	.2737

TABLE 23. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR PRECHAMBER LINER NO. 6 (EX-115861).

PRECHAMBER LINER NO. 6, EX-115861, NOZZLE EX-114779 RIG 9-26-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1544.	0.15	72.52	2.553	15.069	3.236	20.858	0.00
1546.	0.00	106.95	0.688	7.108	6.416	14.212	0.00
0.	0.15	0.00	0.000	0.000	0.000	0.000	0.00
1548.	0.45	165.72	0.420	2.871	8.751	12.042	0.00
1549.	0.20	211.89	0.339	1.594	12.604	14.537	0.00
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		127.83	0.575	3.486	9.559	13.619	0.00
PERCENT OF BASELINE		101.26	23.45	14.55	175.89	42.78	

2. The .500-inch covers on the upstream portion of the dilution holes were replaced with .750-inch covers, thus further reducing the dilution air.

Data from the combustor rig test of this liner are summarized in Table 24. For several operating conditions, data were recorded for both main plus pilot flows through the fuel nozzle and for main only. The addition of pilot fuel flow generally increased exhaust concentrations of CH_x, CO, and smoke, but decreased the NO_x concentrations. The exhaust pattern was unaffected by pilot fuel rates, but the liner skin temperatures generally decreased with increasing pilot fuel rates. Skin temperatures around the reaction zone were measured at 1750-1900°F for 100% power. Again, the NO_x emissions were quite high, as can be seen from the comparison with baseline NO_x over the LOH duty cycle in Table 25. Three sets of duty cycle emissions also are shown in Table 25, the main and pilot fuel systems in airblast nozzle EX-114779 operating simultaneously, the main airblast fuel system operating alone (no pilot), and main plus pilot systems operating under the same conditions as for the main-system-only data, i.e., without the 75% and 100% power points.

Figure 43. Prechamber Liner No. 7, EX-115864.

TABLE 24. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 7 USING DDA AIRBLAST FUEL NOZZLE EX-114779 AT MODEL 250-C20B ENGINE CONDITIONS (PART 1 OF 2)

	Ground Idle		Operational Idle		25% Power
Pilot Fuel Flow (lb/hr)	.0	19.9	.0	19.8	19.8
A. Emissions					
CO (ppm)	179.2	349.4	142.9	228.1	87.8
C_3H_8 (ppm)	6.2	30.8	2.9	9.2	1.6
NO_x (ppm NO_2)	32.6	21.8	35.5	34.3	55.9
Smoke Number	2.8	3.9	1.2	4.5	10.6
CO_2 (%)	2.55	2.50	2.70	2.75	3.21
B. Gas Analysis					
Comb. Eff. (%)	99.64	99.23	99.73	99.57	99.85
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.098	1.090	1.086	1.126	1.098
C. System Performance					
Pressure Drop (%)	4.31	4.41	4.48	4.49	4.30
T_{max}/T_{avg} (°F/°F)	1.2027	1.1945	1.1811	1.1745	1.1901
Pattern Factor	.2780	.2672	.2484	.2395	.2657

TABLE 24. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 7 USING DDA AIRBLAST FUEL NOZZLE EX-114779 AT MODEL 250-C20B ENGINE CONDITIONS (PART 2 OF 2)

Percent Power	40		55		75	100
Pilot Flow Rate (lb/hr)	.0	20.0	.0	39.9	50.0	50.1
A. Emissions						
CO (ppm)	38.6	43.8	31.2	40.7	22.1	16.2
C_3H_8 (ppm)	1.3	1.4	1.1	1.1	1.3	2.6
NO_x (ppm NO_2)	98.2	99.0	130.7	105.8	208.8	281.1
Smoke Number	.0	.0	.0	4.3	6.9	13.8
CO_2 (%)	3.52	3.52	3.84	3.89	4.69	5.03
B. Gas Analysis						
Comb. Eff. (%)	99.91	99.90	99.91	99.91	99.91	99.90
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.114	1.123	1.123	1.141	1.180	1.116
C. System Performance						
Pressure Drop (%)	4.70	4.66	4.64	4.64	4.38	4.64
T_{max}/T_{avg} (°F/°F)	1.1309	1.1322	1.1262	1.1493	1.1830	1.1784
Pattern Factor	.1853	.1872	.1791	.2113	.2562	.2504

TABLE 25. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR PRECHAMBER LINER NO. 7

PRECHAMBER LINER NO. 7, EX-115864, NOZZLE EX-114779, MAIN + PILOT RIG 10-7-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1596.	0.00	62.33	4.245	30.642	3.137	38.024	3.93
1598.	0.15	72.66	1.211	18.970	4.689	24.870	4.49
1599.	0.00	106.44	0.178	6.166	6.452	12.796	10.55
1600.	0.15	136.81	0.146	2.885	10.695	13.726	0.00
1603.	0.45	162.98	0.109	2.466	10.543	13.118	4.31
1604.	0.20	210.02	0.111	1.158	17.976	19.245	6.86
1605.	0.05	256.96	0.192	0.751	21.425	22.368	13.79
CYCLE TOTALS		159.61	0.196	3.165	12.995	16.356	13.79
PERCENT OF BASELINE		99.72	8.58	13.21	240.79	51.69	

PRECHAMBER LINER NO. 7, EX-115864, NOZZLE EX-114779, MAIN ONLY RIG 10-7-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1595.	0.00	62.12	0.848	15.683	4.686	21.217	2.80
1597.	0.15	73.59	0.371	11.720	4.783	16.874	1.20
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1601.	0.15	136.62	0.132	2.514	10.515	13.161	0.00
1602.	0.45	163.13	0.103	1.890	12.993	14.986	0.00
0.	0.20	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		104.94	0.137	3.046	11.645	14.828	2.80
PERCENT OF BASELINE		100.25	4.01	9.15	235.55	35.59	

PRECHAMBER LINER NO. 7, EX-115864, NOZZLE EX-114779, M+P AT M ONLY RIG 10-7-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1596.	0.00	62.33	4.245	30.642	3.137	38.024	3.93
1598.	0.15	72.66	1.211	18.970	4.689	24.870	4.49
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1600.	0.15	136.81	0.146	2.885	10.695	13.726	0.00
1603.	0.45	162.98	0.109	2.466	10.543	13.118	4.31
0.	0.20	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		104.76	0.231	4.265	9.964	14.460	4.49
PERCENT OF BASELINE		100.08	6.76	12.81	201.53	34.71	

Prechamber Liner No. 8

Only a single change was made to prechamber liner No. 7 to produce prechamber liner No. 8. As can be seen, the liner remains unchanged except for the row of twelve .360-inch-diameter primary holes being closed. This enrichened the liner considerably in the forward end of the reaction zone. Since no other liner areas were changed, this reduction in area increased the pressure drop another 1.0%, to approximately 5.0%.

Combustor performance data for prechamber liner No. 8 are summarized in Table 26. As shown, some different pilot fuel flows through nozzle EX-114779 were also investigated as well as the all main-airblast fuel system noted by zero pilot flows. Closing the primary holes allowed the reaction zone liner-metal temperature to increase severely, to nearly 2000°F at 40% power conditions. Therefore, the test was terminated after 55% power data were recorded, to avoid damaging the liner.

Unburned hydrocarbons and smoke were essentially zero for all data points, and carbon monoxide was quite low also. However, nitrogen oxides concentrations were only slightly affected by closing the primary holes. LOH duty cycle emissions through 55% power are presented in Table 27 for the main-only fuel flows.

The conclusions from this test were that the primary holes in prechamber liner No. 7 provided a significant degree of liner cooling in the reaction zone. Closing these holes in liner No. 8 produced the high skin temperatures experienced. The combination of rich fuel-air mixtures and a large reaction zone volume produced the high NO_x concentrations at high-power operating conditions. The intermediate holes have been effective in improving the exhaust temperature pattern, and changes in the dilution holes will probably further improve the pattern.

Prechamber Liner No. 9

The ninth version of the prechamber combustor liner is shown in Figure 44. The changes in this liner from the previous version, No. 8, are as follows:

1. A row of 36 holes of .125 inch diameter were added at the end of the vaporizer tube to provide additional air for leaning the fuel-air mixture entering the reaction zone and providing some cooling effect for the reaction zone dome.
2. A second reverse-flow, film-cooling baffle was added upstream of the intermediate holes to provide cooling to the cylindrical portion of the reaction zone.

TABLE 26. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 8 USING DDA AIRBLAST FUEL NOZZLE EX-114779 AT MODEL 250-C20B ENGINE CONDITIONS

	Operational Idle			Percent Power			
				25		40	55
Pilot Flow (lb/hr)	.0	18.9	41.9	.0	31.6	.0	.0
A. Emissions							
CO (ppm)	119.9	135.2	175.0	62.0	75.6	39.6	30.2
C_3H_8 (ppm)	.3	.1	1.8	.1	.1	.4	.8
NO_x (ppm NO_2)	33.9	33.1	37.8	69.2	55.9	86.9	110.6
Smoke Number	1.2	2.9	6.9	.0	2.5	.0	.0
CO_2 (%)	2.70	2.65	2.70	3.06	3.00	3.31	3.57
B. Gas Analysis							
Comb. Eff. (%)	99.77	99.75	99.68	99.88	99.86	99.90	99.91
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.093	1.090	1.091	1.045	1.044	1.054	1.057
C. System Performance							
Pressure Drop(%)	5.04	5.20	4.82	4.78	5.17	5.06	5.33
T_{max}/T_{avg} (°F/°F)	1.2315	1.1936	1.1924	1.2289	1.2208	1.2033	1.1989
Pattern Factor	.3153	.2634	.2607	.3158	.3056	.2838	.2810

TABLE 27. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR PRECHAMBER LINER NO. 8

PRECHAMBER LINER NO. 8, EX-115865, NOZZLE EX-114779, MAIN ONLY RIG 10-29-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1621.	0.15	72.75	0.040	9.908	4.599	14.547	1.17
1624.	0.00	105.42	0.009	4.357	7.988	12.354	0.00
1626.	0.15	136.88	0.043	2.597	9.354	11.994	0.00
1627.	0.45	164.20	0.080	1.844	11.092	13.016	0.00
0.	0.20	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		105.33	0.069	2.826	10.081	12.975	1.17
PERCENT OF BASELINE		100.63	2.01	8.49	203.89	31.14	

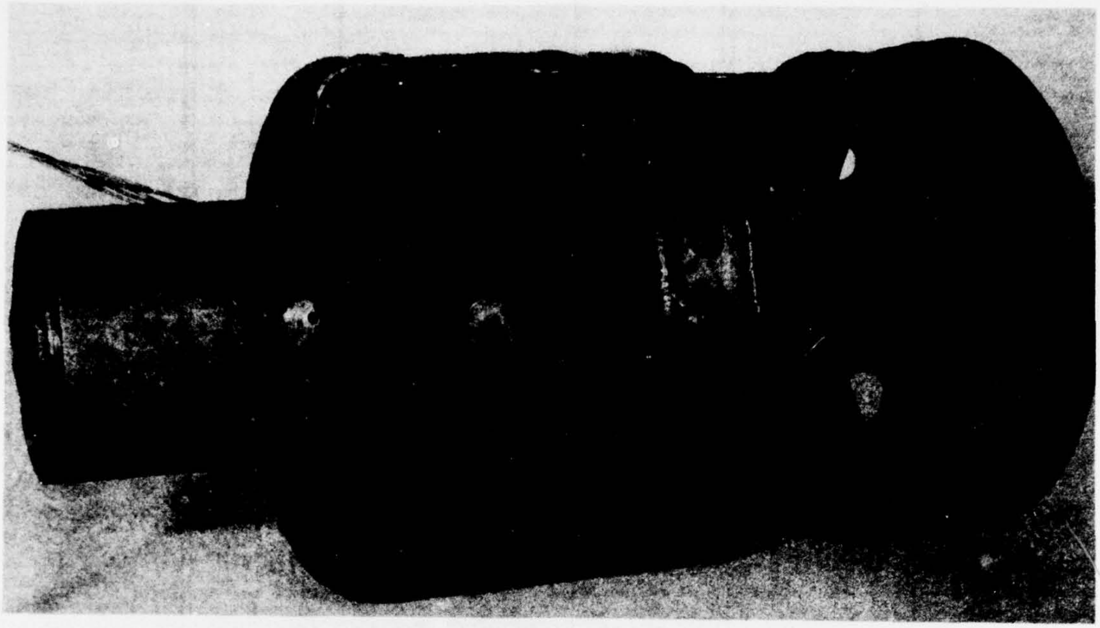

Figure 44. Prechamber Liner No. 9, EX-115888.

3. The twelve intermediate holes were enlarged to .500 inch for the two top and bottom holes, and to .438 inch for the four holes on each side. This change was to produce deeper penetration into the gas leaving the reaction zone to improve the mixing and homogeneity of the intermediate zone.
4. The dilution-hole pattern was returned to an equally-spaced six-hole pattern of .8125 inch in diameter holes.

Data from the combustor rig test of this liner are summarized in Table 28. At operational idle conditions, data were recorded for both main with pilot flow and for main flow only. The addition of pilot fuel flow further increased exhaust CO and CH_x concentrations. The exhaust pattern was also slightly degraded by pilot fuel. Liner metal temperatures decreased significantly with the additional cooling.

The additional air injected into the reaction zone reduced the fuel-air mixture in this region, producing fuel-lean combustion with its high concentrations of CH_x and CO at idle, which exceeded the idle concentrations of the baseline liner. By 25% power conditions, the combustion character changed from fuel lean to fuel rich, as shown by the sizeable drop in CH_x

TABLE 28. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 9 USING DDA AIRBLAST FUEL NOZZLE EX-114779 AT MODEL 250-C20B ENGINE CONDITIONS

	Operational Idle		Percent Power			
			25	40	55	75
Pilot Fuel Flow (lb/hr)	.0	40.1	.0	.0	.0	.0
A. Emissions						
CO (ppm)	1242.5	1734.7	362.5	411.5	112.4	53.4
C_3H_8 (ppm)	490.8	797.2	36.0	22.7	2.9	.7
NO_x (ppm NO_2)	10.7	9.7	39.8	46.5	66.3	93.1
Smoke Number	.0	.0	.0	.0	.8	.8
CO_2 (%)	2.16	2.06	2.98	3.16	3.52	4.11
B. Gas Analysis						
Comb. Eff. (%)	95.60	93.52	99.31	99.32	99.82	99.91
$F\text{-}A_{chem}/F\text{-}A_{mech}$	.997	1.003	1.045	1.018	1.033	1.025
C. System Performance						
Pressure Drop (%)	3.47	3.77	3.64	3.78	3.64	3.73
T_{max}/T_{avg} (°F/°F)	1.1916	1.2353	1.2083	1.2181	1.2122	1.2479
Pattern Factor	.2742	.3432	.2990	.3162	.3088	.3544

and CO emissions to below baseline levels and by the increase of NO_x above baseline levels. Emissions were summed over the LOH duty cycle for this prechamber liner as shown in Table 29. All of these data are for main fuel system only, no pilot fuel was used.

Prechamber Liner No. 10

The tenth version of the prechamber combustor liner is shown in Figure 45. Compared with liner No. 9, there was only one change to the liner hardware: the closing of the thirty-six .125-inch diameter holes at the end of the prechamber.

Data from the combustor rig test of this liner are summarized in Table 30. At operational idle conditions, data were recorded for both main with pilot flows and for main flow only. The addition of pilot fuel flow increased exhaust concentrations of CH_x and CO, but decreased NO_x concentrations slightly. The exhaust pattern was unaffected by pilot fuel rates, but the liner skin temperatures decreased with increasing pilot fuel flow rates.

Eliminating the air injected at the end of the prechamber enrichened the fuel-air mixture in the reaction zone so that more of the unburned hydrocarbons and carbon monoxide were reacted. The higher temperatures also raised the nitrogen oxides concentrations, however. Exhaust smoke was measurable at low power, but reduced to zero at high-power levels. Emissions were summed over the LOH duty cycle for this prechamber liner No. 10, as shown in Table 31. All of these data are for the main fuel system only; no pilot fuel was used.

Prechamber Liner No. 11

Except for the prechamber swirler and vaporizer tube details, all new hardware was used to fabricate Prechamber liner No. 11. The following are the changes from the previous design:

1. The prechamber was shortened from 3.00 to 2.00 inches, and a new airblast fuel injector, EX-115870A, was used.
2. Reaction zone dome cooling air was added through the dome sheet metal against a flow-directing baffle.
3. The reaction zone length was reduced, and the intermediate holes were moved radially inward to the sheet metal diameter of the dilution holes.

TABLE 29. TIME-WEIGHT-AVERAGED LOH DUTY FOR CYCLE EMISSIONS FOR PRECHAMBER LINER NO. 9

PRECHAMBER LINER NO. 9, EX-115888, NOZZLE EX-114779, MAIN ONLY RIG 11-8-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1668.	0.15	72.00	65.010	104.530	1.480	171.020	0.00
1670.	0.00	107.28	4.034	25.771	4.209	34.014	0.00
1671.	0.15	134.02	2.339	26.944	4.660	33.943	0.00
1672.	0.45	166.26	0.276	6.797	5.963	13.036	0.83
1673.	0.20	217.01	0.059	2.767	7.611	10.437	0.82
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		149.12	5.179	15.418	5.942	26.540	0.83
PERCENT OF BASELINE		101.47	209.00	59.39	113.22	78.78	

TABLE 30. COMBUSTION SYSTEM PERFORMANCE OF THE PRECHAMBER LINER NO. 10 OPERATING ON DDA AIRBLAST FUEL NOZZLE EX-114779 WITH MAIN FUEL ONLY (PILOT FUEL ZERO) AT MODEL 250-C20B ENGINE CONDITIONS

	Operational Idle		Percent Power				
	Pilot Flow (lb/hr) 0.0	20.1	25	40	55	75	100
A. Emissions							
CO (ppm)	651.5	892.7	257.6	131.3	60.9	37.5	21.1
C_3H_8 (ppm)	82.1	153.8	8.2	1.7	.5	.3	.4
NO_x (ppm NO_2)	21.3	19.5	36.1	54.8	83.0	103.1	141.4
Smoke Number	10.1	9.8	14.8	9.8	.0	.0	.0
CO_2 (%)	2.55	2.50	3.03	3.36	3.73	4.16	4.78
B. Gas Analysis							
Comb. Eff. (%)	98.53	97.34	99.56	99.79	99.89	99.92	99.93
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.096	1.077	1.060	1.065	1.097	1.058	1.041
C. System Performance							
Pressure Drop (%)	3.92	3.79	3.83	3.83	3.83	4.11	4.13
T_{max}/T_{avg} (°F/°F)	1.1928	1.2114	1.1864	1.1763	1.1814	1.1775	1.1654
Pattern Factor	.2716	.2993	.2665	.2537	.2632	.2549	.2356

TABLE 31. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR PRECHAMBER LINER NO. 10

PRECHAMBER LINER NO. 10, EX-115893, NOZZLE EX-114779, MAIN ONLY RIG 12-4-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1704.	0.15	71.84	10.991	55.422	2.974	69.387	10.08
1706.	0.00	106.99	0.926	18.391	4.229	23.546	14.81
1707.	0.15	136.51	0.173	8.540	5.850	14.563	9.83
1708.	0.45	164.51	0.048	3.699	8.273	12.020	0.00
1709.	0.20	210.54	0.022	1.979	8.936	10.937	0.00
1710.	0.05	265.86	0.026	0.961	10.581	11.568	0.00
CYCLE TOTALS		160.68	0.789	7.107	7.974	15.870	14.81
PERCENT OF BASELINE		100.39	34.50	29.67	147.75	50.16	

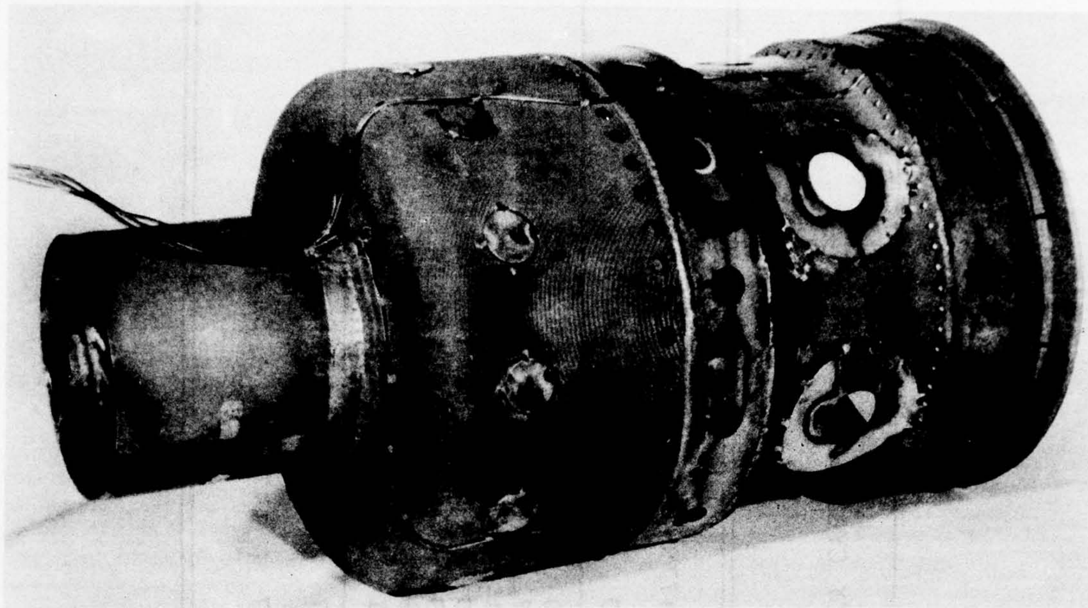

Figure 45. Prechamber Liner No. 10, EX-115893.

4. The cooling baffle between the intermediate and dilution holes was eliminated.
5. The dilution holes were moved upstream an additional inch, from 2.54 to 3.50 inches, from the rear seal.

A photograph of this liner can be seen in Figure 46.

Combustor performance data for prechamber liner No. 11 are summarized in Table 32. As shown there, some different pilot fuel flows through nozzle EX-115870A were investigated as well as the all-main airblast fuel system. Unburned hydrocarbons and carbon monoxide were quite low for all data points. Nitrogen oxides concentrations were high, especially when no pilot fuel was used. Smoke was high only at idle when no pilot was used. LOH duty cycle emissions through 75% power are presented in Table 33 for operation of the fuel nozzle with no pilot fuel flow. Emissions were quite low for CH_x and CO, but again NO_x emissions were high, as was smoke, at idle. Exhaust temperature patterns were about the same as for the previous design, except that high power gave a worsening trend. With the quantity of cooling air used in prechamber liner No. 11,

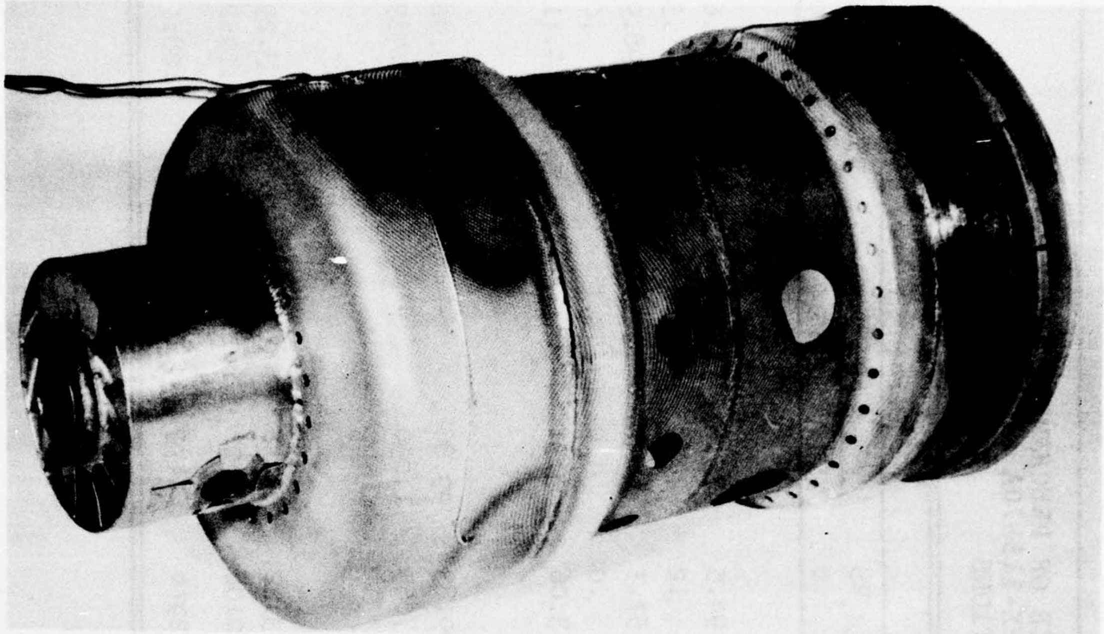

Figure 46. Prechamber Liner No. 11, EX-115894.

the only region showing high temperatures was between the intermediate and dilution holes, where the metal was cooled by only inlet air impingement through the outer case basket. A thermocouple measuring metal temperature in this region read 1650°F at 75% power conditions.

Airblast fuel nozzle EX-115870 is shown in Figure 47. This was the final fuel nozzle configuration, used during the balance of the rig testing and throughout the engine testing. Three versions were used, EX-115870A, B, and C, which differed only in the size of the simplex pilots, having flow numbers of 2.5, 3.5, and 4.0 respectively. The pilots were for operation with the modified conventional combustors, although some data were taken with prechamber combustors operating on main fuel flow with scheduled amounts of pilot flow. The difference between this nozzle and the previous nozzle, EX-114779, was a change only in the atomization method in the pilot. Nozzle EX-114774 impinged a high velocity fuel jet on a fine mesh screen to breakup the fuel, whereas nozzle EX-115870 used a conventional simplex pilot tip.

TABLE 32. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 11 USING AIRBLAST FUEL NOZZLE EX-115870A AT MODEL 250-C20B ENGINE CONDITIONS

	Operational Idle		Percent Power 25	40		55	75
Pilot Flow Rate (lb/hr)	.0	20.0	.0	.0	30.0	.0	.0
A. Emissions							
CO (ppm)	242.5	369.2	94.5	75.6	108.6	59.9	38.6
C_3H_8 (ppm)	6.2	14.2	.2	.9	.6	.3	.3
NO_x (ppm NO_2)	30.8	24.1	57.7	66.1	50.6	76.6	98.9
Smoke Number	38.2	37.0	.0	.0	49.1	.0	.0
CO_2 (%)	2.60	2.55	3.06	3.31	-	3.57	4.11
B. Gas Analysis							
Comb. Eff. (%)	99.53	99.27	99.83	99.86	-	99.89	99.92
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.082	1.064	1.065	1.050	-	1.042	1.039
C. System Performance							
Pressure Drop (%)	3.22	3.08	3.22	3.38	3.43	3.33	3.29
T_{max}/T_{avg} (°F/°F)	1.1827	1.1504	1.2108	1.1727	1.1145	1.1685	1.1962
Pattern Factor	.2529	.2084	.2974	.2479	.1643	.2432	.2811

TABLE 33. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR PRECHAMBER LINER NO. 11

PRECHAMBER LINER NO. 11, EX-115894, NOZZLE EX-115870A, MAIN ONLY RIG 12-16-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1754.	0.15	70.56	0.818	20.477	4.269	25.564	38.22
1756.	0.00	106.35	0.023	6.755	6.777	13.555	0.00
1757.	0.15	136.35	0.089	4.937	7.087	12.113	0.00
1759.	0.45	166.94	0.031	3.602	7.573	11.206	0.00
1760.	0.20	216.07	0.028	2.024	8.527	10.579	0.00
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		149.37	0.094	4.524	7.548	12.166	38.22
PERCENT OF BASELINE		101.64	3.79	17.43	143.82	36.11	

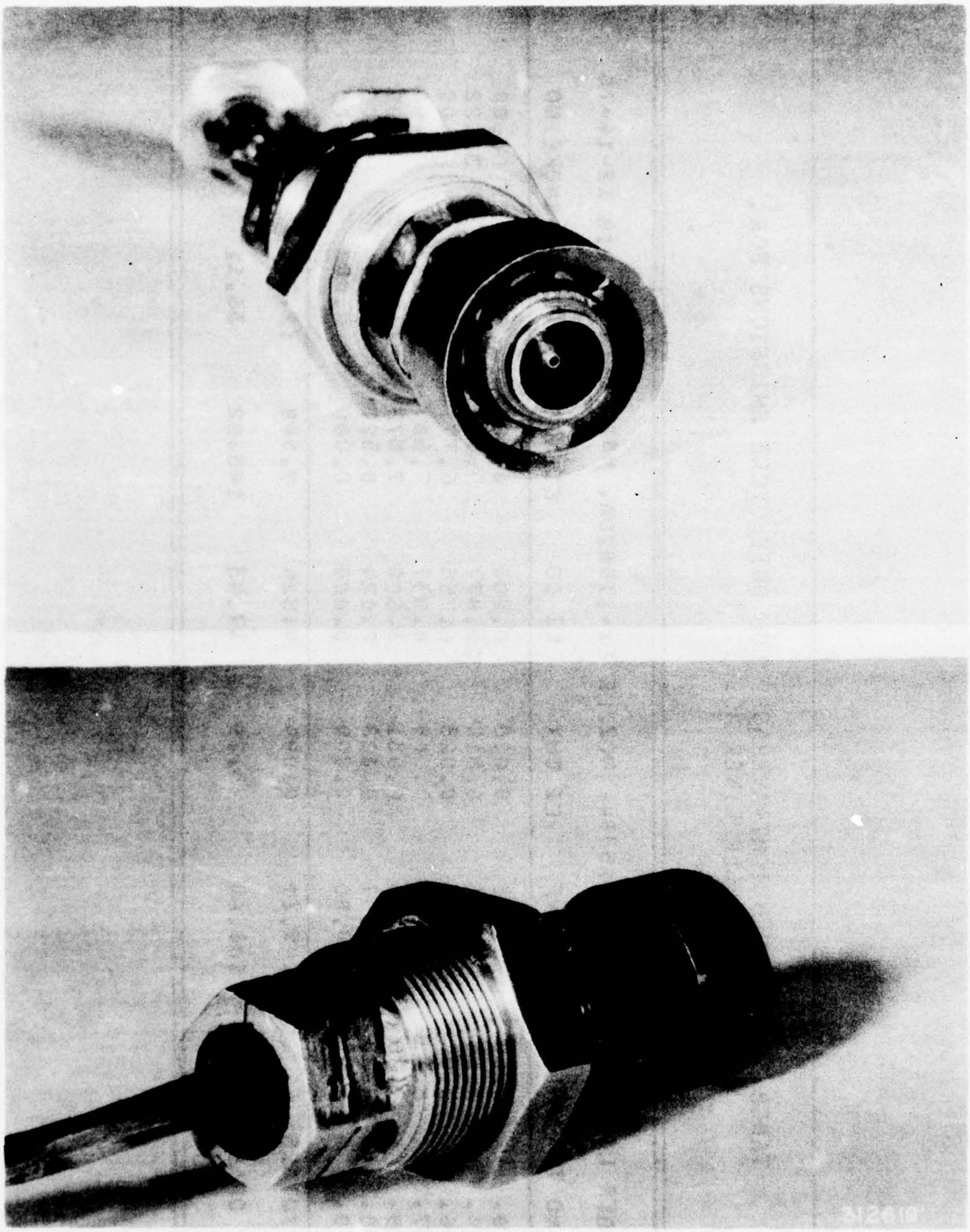

Figure 47. Airblast Fuel Nozzle EX-115870.

Prechamber Liner No. 12

The twelfth version of the prechamber combustor liner is shown in Figure 48. The changes in this liner from the previous version, No. 11, are as follows:

1. Based on the results from the previously tested prechamber, two of every three film cooling holes were closed, since prechamber liner No. 11 was overcooled.
2. To improve the exhaust temperature pattern, the dilution hole diameter in the 5 o'clock position (viewed downstream) was enlarged from 1.00 to 1.25 inches. Also, the dilution hole diameter at the 11 o'clock position was reduced from 1.00 to 0.625 inch. These changes resulted in essentially a zero net area difference from the previous liner dilution area.
3. The pilot tip in the fuel nozzle was changed from a 2.5 flow number in EX-115870A to a 3.5 flow number in EX-115870B.

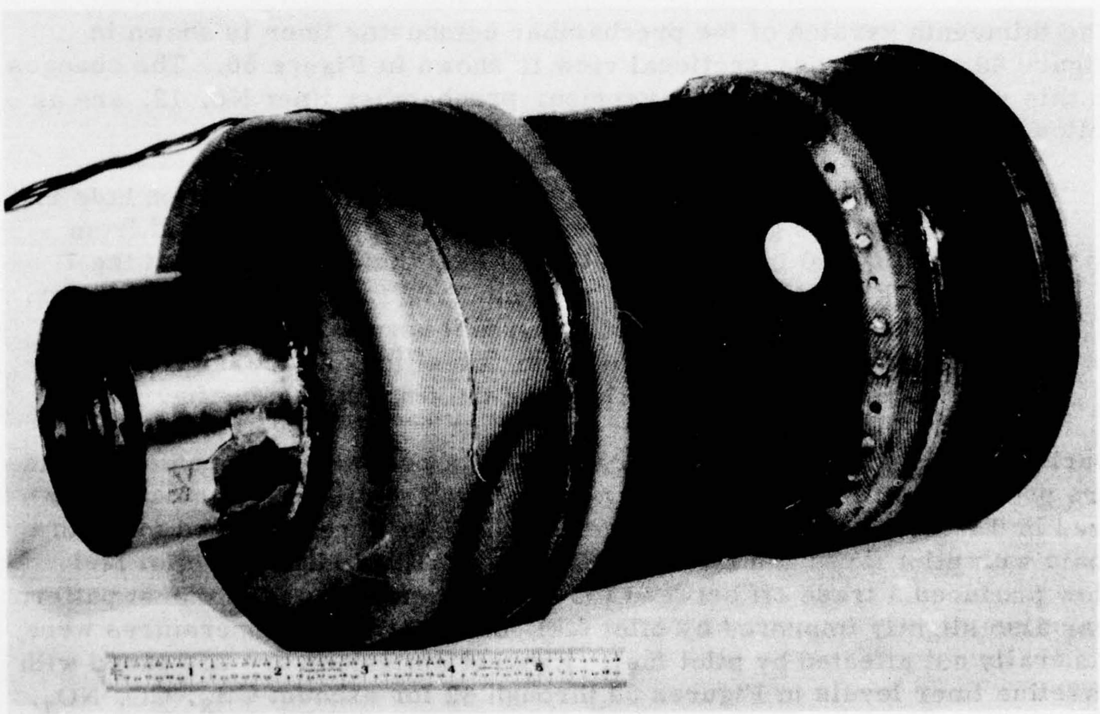

Figure 48. Prechamber Liner No. 12, EX-116290.

Data from the combustor rig test of this liner are summarized in Tables 34 and 35. At several conditions, data were recorded for both main with pilot flows and for main flow only. The addition of pilot fuel flow increased the total exhaust emissions. The exhaust temperature pattern was slightly improved by pilot fuel, but liner skin temperatures were generally unaffected by pilot fuel. Enrichening the reaction zone by closing two-thirds of the cooling holes resulted in an increase of CH_x, CO, and NO_x exhaust emissions simultaneously, but the exhaust smoke was reduced dramatically for main-only operation. Emissions were summed over the LOH duty cycle for prechamber liner No. 12 as shown in Table 36. These first data are for the main fuel system only, through 100% power. The next two sets compare, for like points, main only to main plus pilot systems. Exhaust smoke was essentially zero when only the main fuel system was used. The exhaust temperature pattern had improved over the previous version. Measured liner metal temperatures peaked in the 1700°-1800°F range.

Prechamber Liner No. 13

The thirteenth version of the prechamber combustor liner is shown in Figure 49, and a cross-sectional view is shown in Figure 50. The changes in this liner from the previous version, prechamber liner No. 12, are as follows:

1. To improve the exhaust temperature pattern, the dilution hole in the 3 o'clock position (viewed downstream) was enlarged from .875 to 1.00 inch in diameter. Also, the dilution hole at the 7 o'clock position was reduced from 1.00 to .625 inch in diameter.
2. The 3.5 flow number pilot tip on fuel nozzle EX-115870B was changed to a 4.0 flow number simplex tip, and the nozzle reidentified as EX-115870C. This was the final nozzle configuration.

During the rig testing of this liner, eight data points were documented and are presented in Figures 51 through 58. Data from the test are summarized in Tables 37 and 38. At two conditions data were recorded for both main with pilot flows and for main flow only. The addition of pilot fuel flow produced a trade off between CO and NO_x emissions. Exhaust pattern was also slightly improved by pilot fuel, but liner skin temperatures were generally not affected by pilot fuel. Exhaust emissions are compared with baseline liner levels in Figures 59 through 62 for exhaust CH_x, CO, NO_x, and smoke. All of the exhaust emissions were lower than those from the previous liner version. Emissions were summed over the LOH duty cycle for this prechamber liner, No. 13, as shown in Table 39. These data are for the main fuel system only. Exhaust CH_x for this liner was 1% of baseline, CO was 17%, and NO_x was 156%, and exhaust smoke was zero.

TABLE 34. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 12 USING AIRBLAST FUEL NOZZLE EX-115870B OPERATING ON MAIN FUEL SYSTEM ONLY AT MODEL 250-C20B ENGINE CONDITIONS

	Idle		Percent Power				
	Ground	Operational	25	40	55	75	100
A. Emissions							
CO (ppm)	--	135.2	131.3	112.4	76.7	54.5	26.1
C_3H_8 (ppm)	--	8.0	3.7	2.7	1.1	.5	.2
NO_x (ppm NO_2)	--	52.2	68.6	81.2	95.2	101.1	119.9
Smoke Number	--	.0	.0	.0	.0	.0	2.3
CO_2 (%)	--	2.45	2.90	3.11	3.42	3.89	4.50
B. Gas Analysis							
Comb. Eff. (%)	--	99.68	99.75	99.79	99.85	99.90	99.93
$F\text{-}A_{chem}/F\text{-}A_{mech}$	--	1.018	1.004	.988	.997	.981	.963
C. System Performance							
Pressure Drop (%)	--	3.75	3.75	3.88	3.80	3.71	3.64
T_{max}/T_{avg} (°F/°F)	--	1.166	1.138	1.159	1.142	1.153	1.134
Pattern Factor	--	.2294	.1951	.2274	.2044	.2199	.1899

TABLE 35. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 12 USING AIRBLAST FUEL NOZZLE EX-115870B OPERATING ON MAIN PLUS SCHEDULED PILOT FUEL SYSTEMS AT MODEL 250-C20B ENGINE CONDITIONS

	Idle		Percent Power				
	Ground	Operational	25	40	55	75	100
Pilot Flow Rate (lb/hr)	--	20.3	--	30.0	35.0	40.0	--
A. Emissions							
CO (ppm)	--	179.2	--	119.9	81.8	53.4	--
C_3H_8 (ppm)	--	13.1	--	1.5	4.6	.5	--
NO_x (ppm NO_2)	--	30.2	--	56.5	86.7	101.6	--
Smoke Number	--	25.2	--	42.1	30.2	15.8	--
CO_2 (%)	--	2.45	--	3.06	3.42	3.89	--
B. Gas Analysis							
Comb. Eff. (%)	--	99.59	--	99.79	99.84	99.90	--
$F\text{-}A_{chem}/F\text{-}A_{mech}$	--	1.011	--	.971	.992	.986	--
C. System Performance							
Pressure Drop (%)	--	3.49	--	3.74	3.83	4.00	--
T_{max}/T_{avg} (°F/°F)	--	1.158	--	1.108	1.132	1.146	--
Pattern Factor	--	.2188	--	.1533	.1891	.2101	--

TABLE 36. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR PRECHAMBER LINER NO. 12

PRECHAMBER LINER NO. 12, EX-116290, NOZZLE EX-115870B, MAIN ONLY RIG 1-28-75

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1762.	0.15	70.26	1.063	11.424	7.240	19.727	0.00
1763.	0.00	108.28	0.413	9.297	7.977	17.687	0.00
1764.	0.15	134.00	0.276	7.340	8.705	16.321	0.00
1767.	0.45	166.20	0.108	4.615	9.409	14.132	0.00
1768.	0.20	211.44	0.038	2.848	8.669	11.555	0.00
1770.	0.05	261.09	0.012	1.168	8.812	9.992	2.29
CYCLE TOTALS		160.77	0.165	4.657	8.936	13.758	2.29
PERCENT OF BASELINE		100.45	7.23	19.44	165.58	43.49	

PRECHAMBER LINER NO. 12, EX-116290, NOZZLE EX-115870B, MAIN + PILOT RIG 1-28-75

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1761.	0.15	70.15	1.729	15.004	4.151	20.884	25.21
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1765.	0.15	134.14	0.152	7.818	6.050	14.020	42.13
1766.	0.45	166.42	0.438	4.893	8.516	13.847	30.16
1769.	0.20	211.50	0.038	2.806	8.762	11.606	15.84
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		147.83	0.377	5.414	7.940	13.730	42.13
PERCENT OF BASELINE		100.59	15.19	20.85	151.29	40.76	

PRECHAMBER LINER NO. 12, EX-116290, NOZZLE EX-115870B, M ONLY AT M+P RIG 1-28-75

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1762.	0.15	70.26	1.063	11.424	7.240	19.727	0.00
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1764.	0.15	134.00	0.276	7.340	8.705	16.321	0.00
1767.	0.45	166.20	0.108	4.615	9.409	14.132	0.00
1768.	0.20	211.44	0.038	2.848	8.669	11.555	0.00
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		147.72	0.179	4.966	8.947	14.091	0.00
PERCENT OF BASELINE		100.52	7.22	19.13	170.46	41.83	

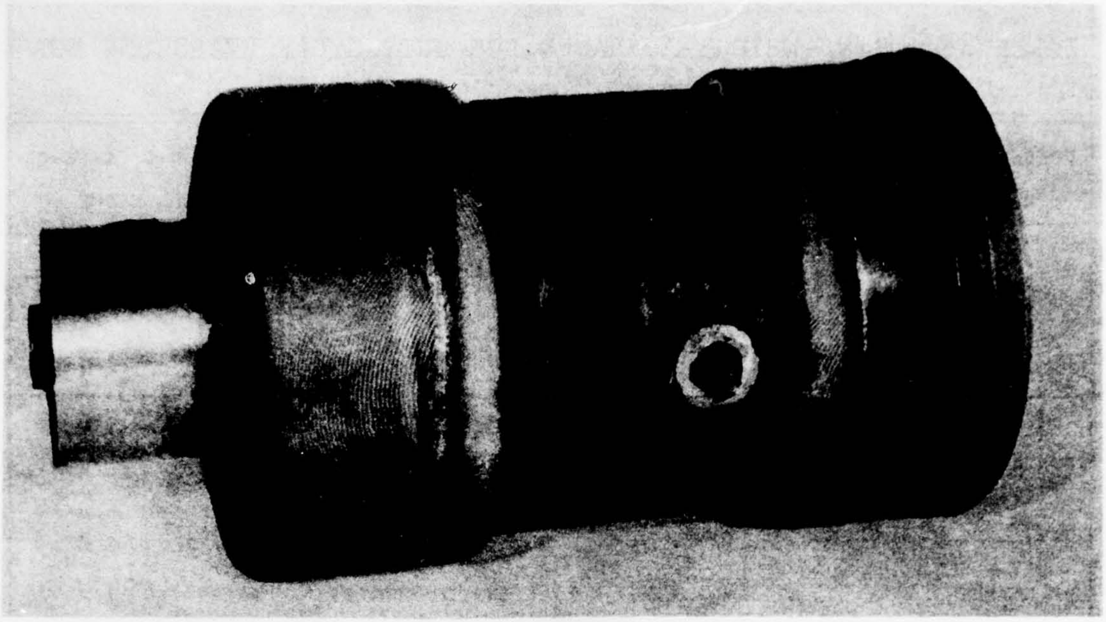

Figure 49. Prechamber Liner No. 13, EX-116291.

Exhaust temperature pattern factors for prechamber liner No. 13 are compared with baseline levels in Figure 63. The pattern was little improved over the previous version. Figures 64 and 65 show the exhaust-annulus, individual thermocouple temperatures measured at 75% and 100% power conditions for main fuel flow only. Although the numerical value of the pattern factor was not improved with this liner version, the distribution of temperatures around the exit annulus was better. Liner-metal temperatures are plotted in Figures 66 and 67 for main only and main plus pilot fuel flows. The high temperatures occur between the rows of intermediate and dilution holes, where there is no effective metal cooling.

Summaries of all prechamber liners' performances are given in Tables 40, 41, and 42 for LOH duty cycle emissions, pattern and liner metal temperatures, and pressure drop. Also, Table 43 summarizes the hole patterns, the pertinent lengths, and the cross-sectional diameters of each of the thirteen prechamber liners tested during the combustor rig development phase of the program.

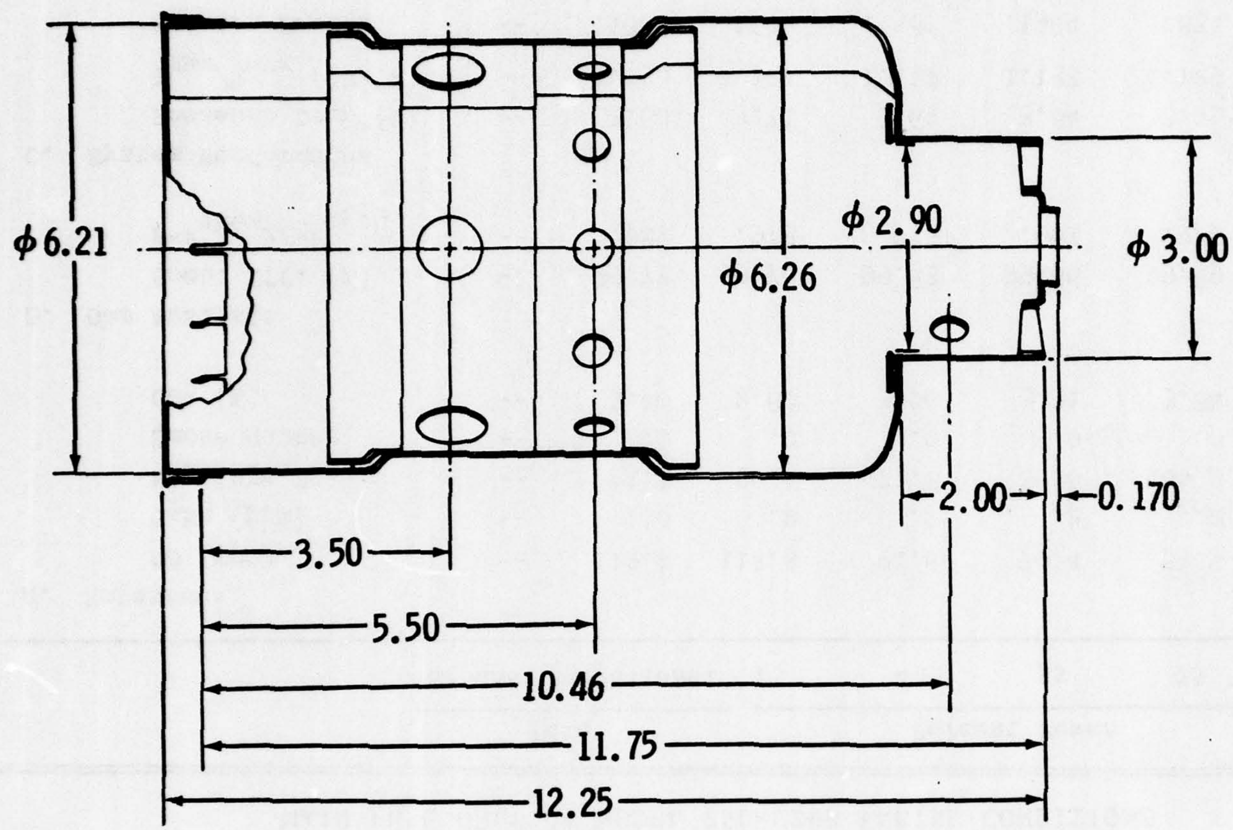

Figure 50. Prechamber Liner No. 13, Cross-Sectional View.

TABLE 37. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 13 USING AIRBLAST FUEL NOZZLE EX-115870C WITH MAIN FUEL ONLY AT MODEL 250-C20B ENGINE CONDITIONS

	Idle		Percent Power				
	Ground	Operational	25	40	55	75	100
A. Emissions							
CO (ppm)	--	112.4	114.3	91.6	70.4	54.5	28.2
C_3H_8 (ppm)	--	1.0	.2	.2	.2	.2	.4
NO_x (ppm NO_2)	--	41.1	56.4	71.8	86.6	104.0	128.0
Smoke Number	--	.0	.0	.0	.0	.0	.0
CO_2 (%)	--	2.40	2.80	3.06	3.31	3.84	4.55
B. Gas Analysis							
Comb. Eff. (%)	--	99.75	99.78	99.83	99.86	99.89	99.93
$F\text{-}A_{chem}/F\text{-}A_{mech}$	--	.987	.973	.973	.961	.975	.982
C. System Performance							
Pressure Drop (%)	--	3.60	3.71	3.69	3.84	3.95	3.85
T_{max}/T_{avg} (°F/°F)	--	1.136	1.121	1.112	1.133	1.129	1.136
Pattern Factor	--	.1866	.1694	.1587	.1904	.1834	.1927

TABLE 38. COMBUSTION SYSTEM PERFORMANCE OF PRECHAMBER LINER NO. 13 USING AIRBLAST FUEL NOZZLE EX-115870C WITH MAIN ONLY AND MAIN PLUS PILOT FUEL SYSTEMS AT MODEL 250-C20B ENGINE CONDITIONS

	Operational Idle		40% Power	
Pilot Flow Rate (lb/hr)	0.	20.	0.	40.
A. Emissions				
CO (ppm)	112.4	223.4	91.6	116.2
C_3H_8 (ppm)	1.0	1.1	.2	.2
NO_x (ppm NO_2)	41.1	25.2	71.8	50.4
Smoke Number	.0	24.7	.0	44.7
CO_2 (%)	2.40	2.40	3.06	3.00
B. Gas Analysis				
Comb. Eff. (%)	99.75	99.55	99.83	99.80
$F\text{-}A_{chem}/F\text{-}A_{mech}$	.987	.989	.973	.957
C. System Performance				
Pressure Drop (%)	3.60	3.57	3.69	3.64
T_{max}/T_{avg} (°F/°F)	1.136	1.127	1.112	1.102
Pattern Factor	.1866	.1741	.1587	.1439

TABLE 39. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR THE PRECHAMBER LINER NO. 13

PRECHAMBER LINER NO. 13, EX-116291, NOZZLE EX-115870C, MAIN ONLY RIG 2-6-75

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1791.	0.15	70.56	0.135	9.412	5.658	15.205	0.00
1793.	0.00	106.88	0.018	8.122	6.580	14.720	0.00
1794.	0.15	131.82	0.017	5.974	7.688	13.679	0.00
1797.	0.45	166.47	0.019	4.215	8.507	12.741	0.00
1798.	0.20	213.89	0.014	2.868	8.988	11.870	0.00
1799.	0.05	263.01	0.027	1.269	9.476	10.772	0.00
CYCLE TOTALS		161.20	0.026	4.174	8.426	12.626	0.00
PERCENT OF BASELINE		100.71	1.12	17.42	156.13	39.91	

```
       COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 173, TEST SERIES -A  , READING #  1791
   C-200 LINER, P/N EX 116291, NOZZLE P/N EX 115870C, JP-4 FUEL.
TEST DATE: 02/06/75                               TIME OF DAY: 1224:14 HOURS

CYCLE POINT  2   .                                          OPERATIONAL IDLE
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          1.678 LB/SEC    AVG BURNER INLET TEMP   302. DEG F
AVG BURNER INLET PRES   45.3    PSIA     AVG BURNER OUTLET TEMP 1118. DEG F
AVG BURNER DELTA P       3.32   "HG      PRESSURE LOSS              3.60 %
OVERALL F/A RATIO       .01108  (F/M)    FUEL FLOW RATE            70.56 LB/HR
AIR LOAD FACTOR         1.0231           PATTERN FACTOR          .18655
BOT HOT SPOT:  # 22 = 1270.  DEG F       MAX BOT / AVG BOT       1.1361
FUEL INLET TEMPERATURE  63.  DEG F       FUEL INLET PRESSURE       46.5  PSIA
HEAT LOADING PARAMETER  .43617E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************* BURNER OUTLET TEMPERATURE SURVEY *******************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1214. 24 1210. 27 1048. 30 1087. 33 1218. 36 1191. 39 1139.
ANNULUS 2 22 1270. 25 1194. 28 1064. 31 1052. 34 1237. 37 1162. 40 1095.
ANNULUS 3 23 1229. 26  926. 29 1004. 32  951. 35 1166. 38  939. 41 1079.

 LEFT SIDE ************* AIR INLET TUBE CONDITIONS ************* RIGHT SIDE
TOTAL PRESSURE           45.27   PSIA   TOTAL PRESSURE           45.26   PSIA
AIR TEMPERATURE          302.  DEG F    AIR TEMPERATURE          302.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................      44.98   PSIA

AIR FLOW DATA: P-REF= 115.3 PSIA   DELTA P= 1.06 "HG    T-REF=  33. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY         255.      HZ    VOLUMETRIC FLOW RATE  11.11 GAL/HR
FUEL PRESSURE AT F/M    285.2    PSIA    FUEL TEMP AT F/M           57.  DEG F
-------------------------------------------------------------------------
                        SKIN TEMPERATURE SURVEY:
 #44=  926. DEG F  #45= 1304. DEG F  #46=  926. DEG F  #47= 1020. DEG F
 #48=  891. DEG F  #
-------------------------------------------------------------------------
    GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
  CHEMICAL F/A RATIO:  .011529    COMBUSTION EFFICIENCY:  99.7536 %
 MEASURED CO2: 2.401 %   MEASURED O2: 16.70 %   CALCULATED O2: 17.65 %
ANALYSIS CHECK: F/A IS  .012066 WHEN CALCULATED USING MEASURED O2 VALUE
    ---------------------------------------------------------
                      EMISSIONS MEASUREMENTS
         CONCENTRATION  EMISSIONS INDEX         INSTRUMENT
             PPM         LB/1000 LB FUEL           SOURCE
    ---------------------------------------------------------
     CO      112.39            9.412            BECKMAN NDIR
    CHX        1.02             .135            BECKMAN  FID
    ---------------------------------------------------------
     NO       36.15            4.972        AMI  CHEMILUMINESCENCE
    NOX       41.13            5.658        AMI  CHEMILUMINESCENCE
    ---------------------------------------------------------
     NO       40.32            5.545            BECKMAN NDIR
    NOX       47.56            6.541        BECKMAN  (NDIR + NDUV)
    ---------------------------------------------------------
      ABSOLUTE HUMIDITY =  4.36 GRAINS PER POUND OF DRY AIR
              SMOKE NUMBER =   .00
NO PILOT.
```

Figure 51. Prechamber Liner No. 13 Rig Data at Operational Idle, Main Flow Only.

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         COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 173, TEST SERIES -A  , READING #  1792
    C-205 LINER, P/N EX 116291, NOZZLE P/N EX 115870C, JP-4 FUEL.
TEST DATE: 02/06/75                            TIME OF DAY: 1234:12 HOURS

CYCLE POINT  2                                           OPERATIONAL IDLE
************************ EXPERIMENTAL  CONDITIONS ***********************
BURNER AIR FLOW          1.666 LB/SEC    AVG BURNER INLET TEMP    305. DEG F
AVG BURNER INLET PRES  45.0    PSIA      AVG BURNER OUTLET TEMP 1132. DEG F
AVG BURNER DELTA P      3.27    "HG      PRESSURE LOSS             3.57 %
OVERALL F/A RATIO      .01171  (F/M)     FUEL FLOW RATE           70.25 LB/HR
AIR LOAD FACTOR        1.0229            PATTERN FACTOR          .17412
BOT HOT SPOT:  # 35 = 1276.  DEG F       MAX BOT / AVG BOT       1.1273
FUEL INLET TEMPERATURE  64.  DEG F       FUEL INLET PRESSURE      45.7  PSIA
HEAT LOADING PARAMETER  .43058E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY *******************
            ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1239. 24 1226. 27 1027. 30 1101. 33 1236. 36 1276. 39 1162.
ANNULUS 2 22 1270. 25 1212. 28 1043. 31 1086. 34 1271. 37 1184. 40 1078.
ANNULUS 3 23 1232. 26  917. 29  928. 32 1072. 35 1219. 38  973. 41 1018.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE            45.03   PSIA    TOTAL PRESSURE          45.02   PSIA
AIR TEMPERATURE           304.  DEG F    AIR TEMPERATURE          305.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE......................  44.66   PSIA

AIR FLOW DATA: P-REF= 115.2 PSIA   DELTA P= 1.04 "HG    T-REF=  35. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY        254.      HZ    VOLUMETRIC FLOW RATE  11.06 GAL/HR
FUEL PRESSURE AT F/M  298.3   PSIA    FUEL TEMP AT F/M               58.  DEG F
-------------------------------------------------------------------------
                      SKIN TEMPERATURE SURVEY:
 #44=  997. DEG F  #45= 1203. DEG F  #46=  919. DEG F  #47= 1265. DEG F
 #48=  871. DEG F   #
-------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .011582    COMBUSTION EFFICIENCY:  99.5541 %
 MEASURED CO2: 2.401 %   MEASURED O2:  1.00 %   CALCULATED O2: 17.64 %
ANALYSIS CHECK: F/A IS  .053331 WHEN CALCULATED USING MEASURED O2 VALUE
      -------------------------------------------------------------
                       EMISSIONS MEASUREMENTS
         CONCENTRATION  EMISSIONS INDEX         INSTRUMENT
              PPM        LB/1000 LB FUEL          SOURCE
      -------------------------------------------------------------
       CO     223.36          18.655             BECKMAN NDIR
      CHX       1.13            .148             BECKMAN  FID
      -------------------------------------------------------------
       NO      20.05           2.750         AMI  CHEMILUMINESCENCE
      NOX      25.19           3.456         AMI  CHEMILUMINESCENCE
      -------------------------------------------------------------
       NO      21.63           2.967             BECKMAN NDIR
      NOX      28.87           3.960         BECKMAN  (NDIR + NDUV)
      -------------------------------------------------------------
        ABSOLUTE HUMIDITY =  4.36 GRAINS PER POUND OF DRY AIR
              SMOKE NUMBER = 24.68
 PILOT WF= 19.8 LB/HOUR.
```

Figure 52. Prechamber Liner No. 13 Rig Data at Operational Idle, Main Plus Pilot.

```
       COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 173, TEST SERIES -A  , READING #  1793
   C-203 LINER, P/N EX 116291, NOZZLE P/N EX 115870C, JP-4 FUEL.
TEST DATE: 02/06/75                          TIME OF DAY: 1256:10 HOURS

CYCLE POINT  3                                    25% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ***********************
BURNER AIR FLOW          2.153 LB/SEC    AVG BURNER INLET TEMP   374. DEG F
AVG BURNER INLET PRES   59.7   PSIA      AVG BURNER OUTLET TEMP 1319. DEG F
AVG BURNER DELTA P       4.50   "HG      PRESSURE LOSS           3.71 %
OVERALL F/A RATIO       .01379  (F/M)    FUEL FLOW RATE        106.88 LB/HR
AIR LOAD FACTOR         1.0417           PATTERN FACTOR        .16937
BOT HOT SPOT:  # 22 = 1479.  DEG F       MAX BOT / AVG BOT     1.1213
FUEL INLET TEMPERATURE  64.  DEG F       FUEL INLET PRESSURE     69.7  PSIA
HEAT LOADING PARAMETER  .49421E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY *******************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1443. 24 1433. 27 1253. 30 1288. 33 1414. 36 1382. 39 1314.
ANNULUS 2 22 1479. 25 1426. 28 1310. 31 1234. 34 1452. 37 1336. 40 1272.
ANNULUS 3 23 1449. 26 1135. 29 1250. 32 1157. 35 1376. 38 1066. 41 1236.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE         59.67   PSIA     TOTAL PRESSURE          59.71   PSIA
AIR TEMPERATURE        374.   DEG F     AIR TEMPERATURE         374.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................... 58.94   PSIA

AIR FLOW DATA: P-REF= 114.5 PSIA    DELTA P= 1.76 "HG     T-REF= 36. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       385.      HZ      VOLUMETRIC FLOW RATE  16.84 GAL/HR
FUEL PRESSURE AT F/M   292.1     PSIA      FUEL TEMP AT F/M         59.  DEG F
-------------------------------------------------------------------------
                      SKIN TEMPERATURE SURVEY:
 #44=  996. DEG F  #45= 1457. DEG F  #46= 1079. DEG F  #47= 1232. DEG F
 #48=  999. DEG F  #
-------------------------------------------------------------------------
    GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .013412    COMBUSTION EFFICIENCY:  99.7816 %
 MEASURED CO2: 2.801 %   MEASURED O2: 16.80 %   CALCULATED O2: 17.09 %
ANALYSIS CHECK: F/A IS  .013596 WHEN CALCULATED USING MEASURED O2 VALUE
      ---------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
          CONCENTRATION  EMISSIONS INDEX        INSTRUMENT
              PPM         LB/1000 LB FUEL          SOURCE
      ---------------------------------------------------------------
      CO    114.27            8.122              BECKMAN NDIR
      CHX      .16             .018              BECKMAN  FID
      ---------------------------------------------------------------
      NO     50.32            5.875         AMI  CHEMILUMINESCENCE
      NOX    56.36            6.580         AMI  CHEMILUMINESCENCE
      ---------------------------------------------------------------
      NO     53.60            6.258              BECKMAN NDIR
      NOX    61.66            7.199          BECKMAN [NDIR + NDUV]
      ---------------------------------------------------------------
         ABSOLUTE HUMIDITY =   4.36 GRAINS PER POUND OF DRY AIR
                SMOKE NUMBER =   .00

 NO PILOT.
```

Figure 53. Prechamber Liner No. 13 Rig Data at 25% Power.

```
        COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 173, TEST SERIES    -A, READING #  1794
    C20B LINER, P/N EX116291,   NOZZLE P/N EX115870C,  JP-4 FUEL.
TEST DATE: 02/06/75                               TIME OF DAY: 1315:27 HOURS

CYCLE POINT  4                                           40% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW           2.433 LB/SEC    AVG BURNER INLET TEMP    427. DEG F
AVG BURNER INLET PRES   69.3   PSIA     AVG BURNER OUTLET TEMP 1447. DEG F
AVG BURNER DELTA P        5.20   "HG      PRESSURE LOSS              3.69 %
OVERALL F/A RATIO      .01505  (F/M)     FUEL FLOW RATE           131.82 LB/HR
AIR LOAD FACTOR          1.0454           PATTERN FACTOR            .15866
BOT HOT SPOT:  # 25 = 1609.  DEG F      MAX BOT / AVG BOT         1.1118
FUEL INLET TEMPERATURE  63.  DEG F      FUEL INLET PRESSURE        85.4  PSIA
HEAT LOADING PARAMETER  .52500E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1531. 24 1514. 27 1395. 30 1406. 33 1582. 36 1526. 39 1442.
ANNULUS 2 22 1608. 25 1609. 28 1428. 31 1397. 34 1587. 37 1462. 40 1375.
ANNULUS 3 23 1572. 26 1246. 29 1345. 32 1275. 35 1514. 38 1216. 41 1361.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE            69.28   PSIA    TOTAL PRESSURE              69.32   PSIA
AIR TEMPERATURE            427.   DEG F   AIR TEMPERATURE              427.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE......................  68.34   PSIA

AIR FLOW DATA: P-REF= 110.2 PSIA   DELTA P= 2.35 "HG    T-REF=  37. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY         474.       HZ     VOLUMETRIC FLOW RATE  20.75 GAL/HR
FUEL PRESSURE AT F/M  264.0   PSIA     FUEL TEMP AT F/M              58.  DEG F
--------------------------------------------------------------------------
                         SKIN TEMPERATURE SURVEY:
 #44= 1031. DEG F  #45= 1547. DEG F  #46= 1178. DEG F  #47= 1334. DEG F
 #48= 1094. DEG F  #
--------------------------------------------------------------------------
     GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .014595    COMBUSTION EFFICIENCY:  99.8272 %
 MEASURED CO2: 3.055 %   MEASURED O2: 16.50 %   CALCULATED O2: 16.74 %
ANALYSIS CHECK: F/A IS  .014759 WHEN CALCULATED USING MEASURED O2 VALUE
     ----------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
        CONCENTRATION  EMISSIONS INDEX        INSTRUMENT
             PPM         LB/1000 LB FUEL          SOURCE
     ----------------------------------------------------------------
      CO       91.62              5.974             BECKMAN NDIR
     CHX        .16               .017             BECKMAN  FID
     ----------------------------------------------------------------
      NO       63.60              6.812         AMI  CHEMILUMINESCENCE
     NOX       71.79              7.688         AMI  CHEMILUMINESCENCE
     ----------------------------------------------------------------
      NO       67.16              7.193             BECKMAN NDIR
     NOX       75.63              8.100         BECKMAN  [NDIR + NDUV]
     ----------------------------------------------------------------
        ABSOLUTE HUMIDITY =  4.38 GRAINS PER POUND OF DRY AIR
              SMOKE NUMBER =   .00
 NO PILOT.
```

Figure 54. Prechamber Liner No. 13 Rig Data at 40% Power, Main Flow Only.

```
          COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 173, TEST SERIES   -A, READING #  1796
   C208 LINER, P/N EX116291,  NOZZLE P/N EX115870C,  JP-4 FUEL.
TEST DATE: 02/06/75                            TIME OF DAY: 1337:16 HOURS

CYCLE POINT  4                                          40% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          2.586 LB/SEC     AVG BURNER INLET TEMP    425. DEG F
AVG BURNER INLET PRES   73.9    PSIA      AVG BURNER OUTLET TEMP 1455. DEG F
AVG BURNER DELTA P       5.48   "HG       PRESSURE LOSS             3.64 %
OVERALL F/A RATIO      .01502  (F/M)      FUEL FLOW RATE          139.82 LB/HR
AIR LOAD FACTOR        1.0402             PATTERN FACTOR          .14393
BOT HOT SPOT:  # 34 = 1603.   DEG F       MAX BOT / AVG BOT        1.1019
FUEL INLET TEMPERATURE  63.   DEG F       FUEL INLET PRESSURE       81.3  PSIA
HEAT LOADING PARAMETER  .32204E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************* BURNER OUTLET TEMPERATURE SURVEY *******************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1535. 24 1527. 27 1347. 30 1403. 33 1577. 36 1570. 39 1449.
ANNULUS 2 22 1598. 25 1581. 28 1416. 31 1371. 34 1603. 37 1477. 40 1385.
ANNULUS 3 23 1578. 26 1224. 29 1359. 32 1425. 35 1553. 38 1249. 41 1316.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE          73.96   PSIA      TOTAL PRESSURE          73.88   PSIA
AIR TEMPERATURE          425.   DEG F     AIR TEMPERATURE          425.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................  72.80   PSIA

AIR FLOW DATA: P-REF= 113.8 PSIA   DELTA P= 2.58 "HG   T-REF=  39. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY        503.      HZ    VOLUMETRIC FLOW RATE  22.02 GAL/HR
FUEL PRESSURE AT F/M  282.3   PSIA        FUEL TEMP AT F/M         59.  DEG F
-------------------------------------------------------------------------
                     SKIN TEMPERATURE SURVEY:
 #44= 1131. DEG F  #45= 1507. DEG F  #46= 1175. DEG F  #47= 1375. DEG F
 #48= 1072. DEG F  #
-------------------------------------------------------------------------
     GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .014367   COMBUSTION EFFICIENCY:  99.7973 %
 MEASURED CO2: 3.004 %   MEASURED O2: 16.50 %   CALCULATED O2: 16.81 %
ANALYSIS CHECK: F/A IS  .014576 WHEN CALCULATED USING MEASURED O2 VALUE
     ------------------------------------------------------------
                     EMISSIONS MEASUREMENTS
        CONCENTRATION  EMISSIONS INDEX         INSTRUMENT
             PPM       LB/1000 LB FUEL           SOURCE
     ------------------------------------------------------------
      CO     116.15           7.589            BECKMAN NDIR
      CHX       .21            .021            BECKMAN  FID
     ------------------------------------------------------------
      NO      44.39           4.763        AMI  CHEMILUMINESCENCE
      NOX     50.42           5.411        AMI  CHEMILUMINESCENCE
     ------------------------------------------------------------
      NO      44.91           4.820            BECKMAN NDIR
      NOX     54.65           5.864        BECKMAN  [NDIR + NDUV]
     ------------------------------------------------------------
       ABSOLUTE HUMIDITY =  4.36 GRAINS PER POUND OF DRY AIR
            SMOKE NUMBER = 44.66
 PILOT WF= 39.9 LB/HOUR.
```

55. **Prechamber Liner No. 13 Rig Data at 40% Power, Main Plus Pilot.**

```
      COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 173, TEST SERIES    -A, READING #  1797
    C208 LINER, P/N EX116291,  NOZZLE P/N EX115870C,  JP-4 FUEL.
TEST DATE: 02/06/75                               TIME OF DAY: 1358:27 HOURS

CYCLE POINT  5                                         55% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          2.815 LB/SEC    AVG BURNER INLET TEMP    471. DEG F
AVG BURNER INLET PRES  82.2    PSIA      AVG BURNER OUTLET TEMP 1550. DEG F
AVG BURNER DELTA P      6.42   "HG       PRESSURE LOSS             3.84 %
OVERALL F/A RATIO      .01643  (F/M)     FUEL FLOW RATE          166.47 LB/HR
AIR LOAD FACTOR        1.0448            PATTERN FACTOR          .19035
BOT HOT SPOT:  # 22 = 1756.  DEG F       MAX BOT / AVG BOT       1.1326
FUEL INLET TEMPERATURE  63.  DEG F       FUEL INLET PRESSURE      109.1  PSIA
HEAT LOADING PARAMETER  .55910E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1665. 24 1669. 27 1481. 30 1526. 33 1673. 36 1604. 39 1555.
ANNULUS 2 22 1756. 25 1752. 28 1505. 31 1484. 34 1686. 37 1566. 40 1506.
ANNULUS 3 23 1714. 26 1341. 29 1480. 32 1174. 35 1593. 38 1325. 41 1504.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE           82.20   PSIA    TOTAL PRESSURE           82.15   PSIA
AIR TEMPERATURE          470.   DEG F    AIR TEMPERATURE           471.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................  80.94   PSIA

AIR FLOW DATA: P-REF= 112.7 PSIA   DELTA P= 3.10 "HG   T-REF=  41. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY        600.      HZ    VOLUMETRIC FLOW RATE  26.23 GAL/HR
FUEL PRESSURE AT F/M   263.6    PSIA    FUEL TEMP AT F/M           60.  DEG F
--------------------------------------------------------------------------
                      SKIN TEMPERATURE SURVEY:
 #44= 1064. DEG F  #45= 1054. DEG F  #46= 1277. DEG F  #47= 1196. DEG F
 #48= 1280. DEG F  #
--------------------------------------------------------------------------
     GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
  CHEMICAL F/A RATIO:  .015793    COMBUSTION EFFICIENCY:  99.8636 %
 MEASURED CO2: 3.313 %   MEASURED O2: 16.20 %   CALCULATED O2: 16.38 %
ANALYSIS CHECK: F/A IS  .015927 WHEN CALCULATED USING MEASURED O2 VALUE
     ----------------------------------------------------------
                      EMISSIONS MEASUREMENTS
        CONCENTRATION  EMISSIONS INDEX        INSTRUMENT
             PPM        LB/1000 LB FUEL         SOURCE
     ----------------------------------------------------------
      CO      70.45           4.215              BECKMAN NDIR
     CHX        .21            .019              BECKMAN  FID
     ----------------------------------------------------------
      NO      81.31           7.990         AMI  CHEMILUMINESCENCE
     NOX      86.57           8.507         AMI  CHEMILUMINESCENCE
     ----------------------------------------------------------
      NO      79.63           7.625              BECKMAN NDIR
     NOX      87.69           8.617         BECKMAN  [NDIR + NDUV]
     ----------------------------------------------------------
        ABSOLUTE HUMIDITY =  4.36 GRAINS PER POUND OF DRY AIR
             SMOKE NUMBER =   .00
```

Figure 56. Prechamber Liner No. 13 Rig Data at 55% Power.

```
      COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/D 173, TEST SERIES    -A, READING #  1798
   C20B LINER, P/N EX110291,  NOZZLE P/N EX115670C,  JP-4 FUEL.
TEST DATE: 02/06/75                             TIME OF DAY: 1416:55 HOURS

CYCLE POINT  6                                       75% POWER SETTING
************************* EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW         3.173 LB/SEC    AVG BURNER INLET TEMP    515. DEG F
AVG BURNER INLET PRES   92.9    PSIA    AVG BURNER OUTLET TEMP 1724. DEG F
AVG BURNER DELTA P      7.47    "HG     PRESSURE LOSS             3.95 %
OVERALL F/A RATIO     .01672  (F/M)     FUEL FLOW RATE          213.89 LB/HR
AIR LOAD FACTOR        1.0067           PATTERN FACTOR          .18339
BOT HOT SPOT:  # 25 = 1946.  DEG F      MAX BOT / AVG BOT       1.1286
FUEL INLET TEMPERATURE  63.  DEG F      FUEL INLET PRESSURE      139.5  PSIA
HEAT LOADING PARAMETER   .63549E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY *******************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1819. 24 1814. 27 1657. 30 1729. 33 1867. 36 1829. 39 1747.
ANNULUS 2 22 1699. 25 1946. 28 1657. 31 1626. 34 1894. 37 1766. 40 1653.
ANNULUS 3 23 1836. 26 1551. 29 1630. 32 1332. 35 1829. 38 1492. 41 1638.

 LEFT SIDE ************* AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE          92.95   PSIA    TOTAL PRESSURE           92.83   PSIA
AIR TEMPERATURE         515.    DEG F   AIR TEMPERATURE          515.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................     91.08   PSIA

AIR FLOW DATA: P-REF= 110.3 PSIA   DELTA P= 4.05 "HG    T-REF=  42. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       775.       HZ      VOLUMETRIC FLOW RATE  33.71 GAL/HR
FUEL PRESSURE AT F/M   248.3    PSIA    FUEL TEMP AT F/M           60.  DEG F
--------------------------------------------------------------------------
                        SKIN TEMPERATURE SURVEY:
#44= 1159. DEG F   #45= 1707. DEG F   #46= 1385. DEG F   #47= 1150. DEG F
#48= 1400. DEG F   #
--------------------------------------------------------------------------
   GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:   .018246     COMBUSTION EFFICIENCY:  99.8932 %
 MEASURED CO2: 3.640 %   MEASURED O2: 15.30 %   CALCULATED O2: 15.65 %
ANALYSIS CHECK: F/A IS  .018546 WHEN CALCULATED USING MEASURED O2 VALUE
      ------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
          CONCENTRATION  EMISSIONS INDEX          INSTRUMENT
               PPM        LB/1000 LB FUEL           SOURCE
      ------------------------------------------------------------
       CO       54.52            2.868            BECKMAN NDIR
      CHX         .17             .014            BECKMAN  FID
      ------------------------------------------------------------
       NO      104.01            8.988         AMI  CHEMILUMINESCENCE
      NOX      104.01            8.988         AMI  CHEMILUMINESCENCE
      ------------------------------------------------------------
       NO      102.75            8.879            BECKMAN NDIR
      NOX      108.37            9.364         BECKMAN  [NDIR + NDUV]
      ------------------------------------------------------------
        ABSOLUTE HUMIDITY =   4.36 GRAINS PER POUND OF DRY AIR
             SMOKE NUMBER =    .00
NO PILOT.
```

Figure 57. Prechamber Liner No. 13 Rig Data at 75% Power.

```
     COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG 870 1/3, TEST SERIES    -A, READING #  1799
    C200 LINER, P/N EX116291,   NOZZLE P/N EX115870C,   JP-4 FUEL.
TEST DATE: 02/06/75                              TIME OF DAY: 1430:38 HOURS

CYCLE POINT  7                                         100% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          3.334 LB/SEC     AVG BURNER INLET TEMP    570. DEG F
AVG BURNER INLET PRES 103.1    PSIA       AVG BURNER OUTLET TEMP 1918. DEG F
AVG BURNER DELTA P       6.07    "HG      PRESSURE LOSS             3.85 %
OVERALL F/A RATIO      .02192  (F/M)      FUEL FLOW RATE          263.01 LB/HR
AIR LOAD FACTOR        1.0380             PATTERN FACTOR           .19272
BOT HOT SPOT:   # 34 = 2178.   DEG F      MAX BOT / AVG BOT        1.1355
FUEL INLET TEMPERATURE  66.    DEG F      FUEL INLET PRESSURE      175.5  PSIA
HEAT LOADING PARAMETER   .70435E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

****************** BURNER OUTLET TEMPERATURE SURVEY ******************
          ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 2040. 24 1977. 27 1854. 30 1892. 33 2135. 36 2073. 39 1934.
ANNULUS 2 22 2051. 25 2167. 28 1951. 31 1791. 34 2178. 37 2050. 40 1820.
ANNULUS 3 23 1748. 26 1664. 29 1737. 32 1438. 35 2108. 38 1721. 41 1739.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE          103.03   PSIA     TOTAL PRESSURE          103.09   PSIA
AIR TEMPERATURE           570.   DEG F    AIR TEMPERATURE           570.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE..................... 100.90   PSIA

AIR FLOW DATA: P-REF= 112.5 PSIA    DELTA P= 4.41 "HG    T-REF=  45. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       956.      HZ     VOLUMETRIC FLOW RATE  41.53 GAL/HR
FUEL PRESSURE AT F/M  349.3   PSIA        FUEL TEMP AT F/M          63.  DEG F
-------------------------------------------------------------------------
                      SKIN TEMPERATURE SURVEY:
 #44= 1255. DEG F   #45= 1820. DEG F   #46= 1540. DEG F   #47= 1299. DEG F
 #48= 1479. DEG F   #
-------------------------------------------------------------------------
       GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:   .021533     COMBUSTION EFFICIENCY:  99.9276 %
 MEASURED CO2: 4.551 %   MEASURED O2: 14.50 %   CALCULATED O2: 14.66 %
ANALYSIS CHECK: F/A IS  .021693 WHEN CALCULATED USING MEASURED O2 VALUE
       -----------------------------------------------------------
                      EMISSIONS MEASUREMENTS
          CONCENTRATION  EMISSIONS INDEX          INSTRUMENT
               PPM       LB/1000 LB FUEL            SOURCE
       -----------------------------------------------------------
        CO      28.15           1.269            BECKMAN NDIR
        CHX       .38            .027            BECKMAN  FID
       -----------------------------------------------------------
        NO     127.96           9.476        AMI  CHEMILUMINESCENCE
        NOX    127.96           9.476        AMI  CHEMILUMINESCENCE
       -----------------------------------------------------------
        NO     130.00           9.627            BECKMAN NDIR
        NOX    136.43          10.103        BECKMAN  [NDIR + NDUV]
       -----------------------------------------------------------
          ABSOLUTE HUMIDITY =   4.36 GRAINS PER POUND OF DRY AIR
              SMOKE NUMBER =    .00
NO PILOT.
```

Figure 58. Prechamber Liner No. 13 Rig Data at 100% Power.

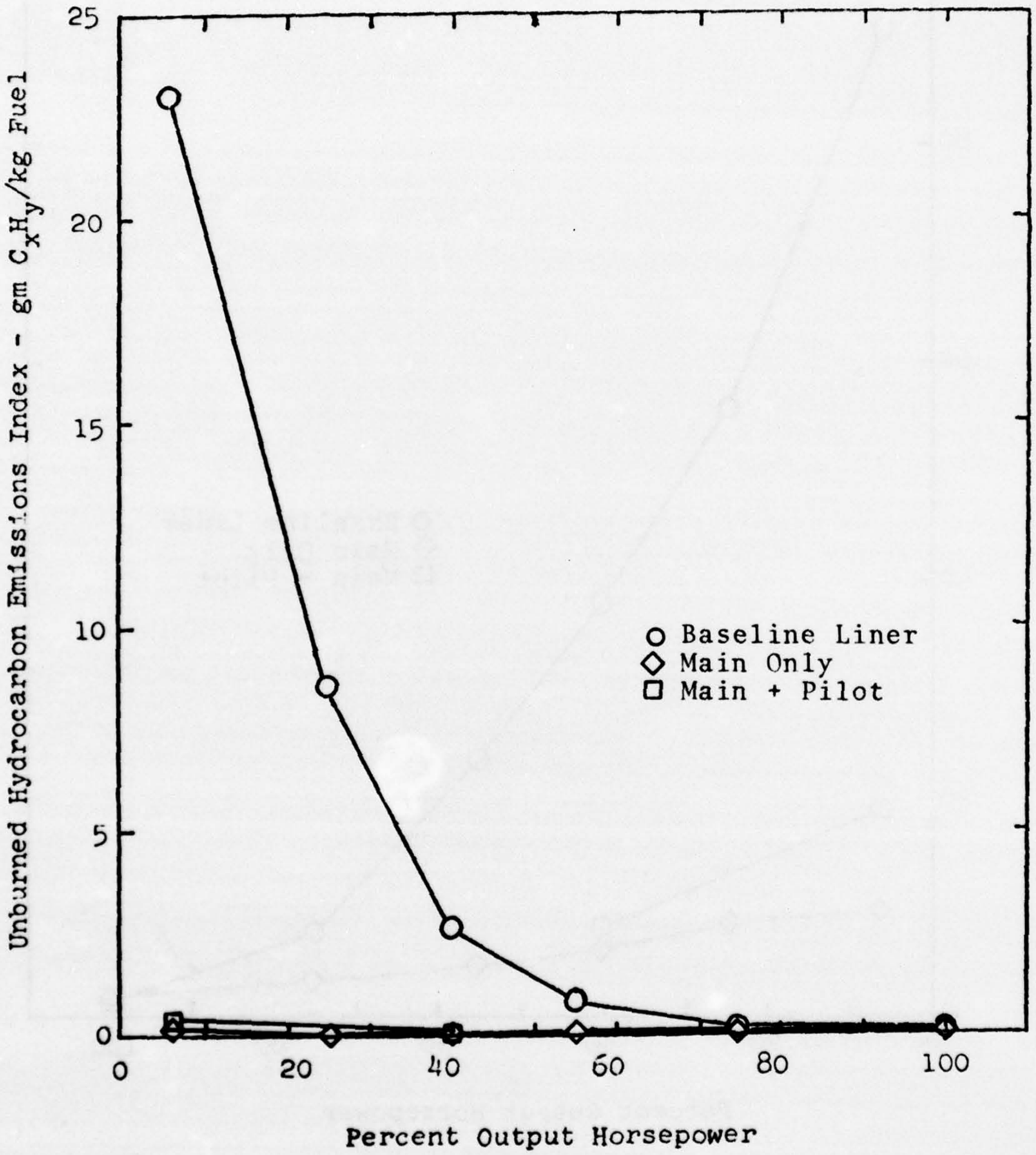

Figure 59. Prechamber Liner No. 13 and Baseline Liner Unburned Hydrocarbon Emissions.

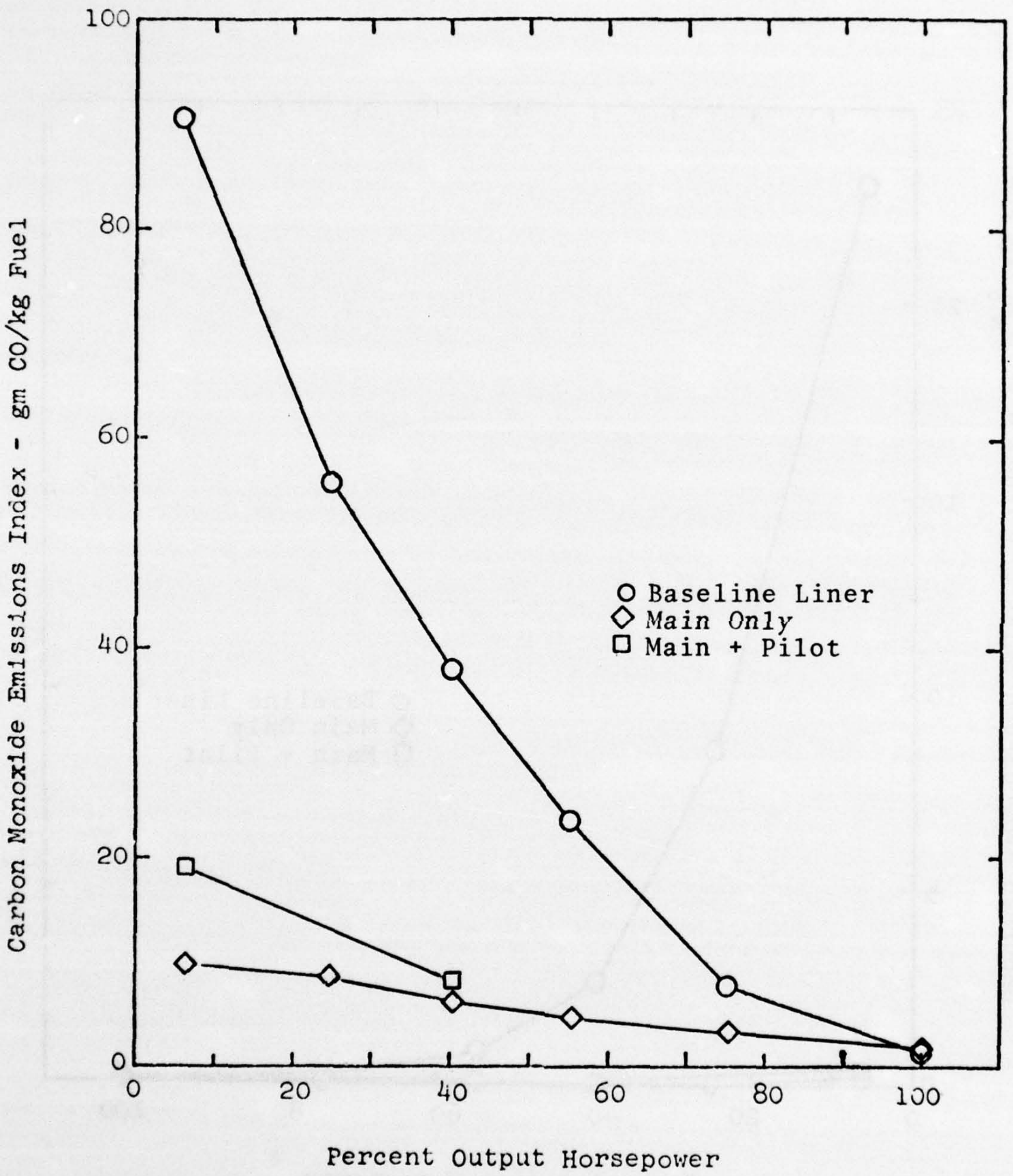

Figure 60. Prechamber Liner No. 13 and Baseline Liner Carbon Monoxide Emissions.

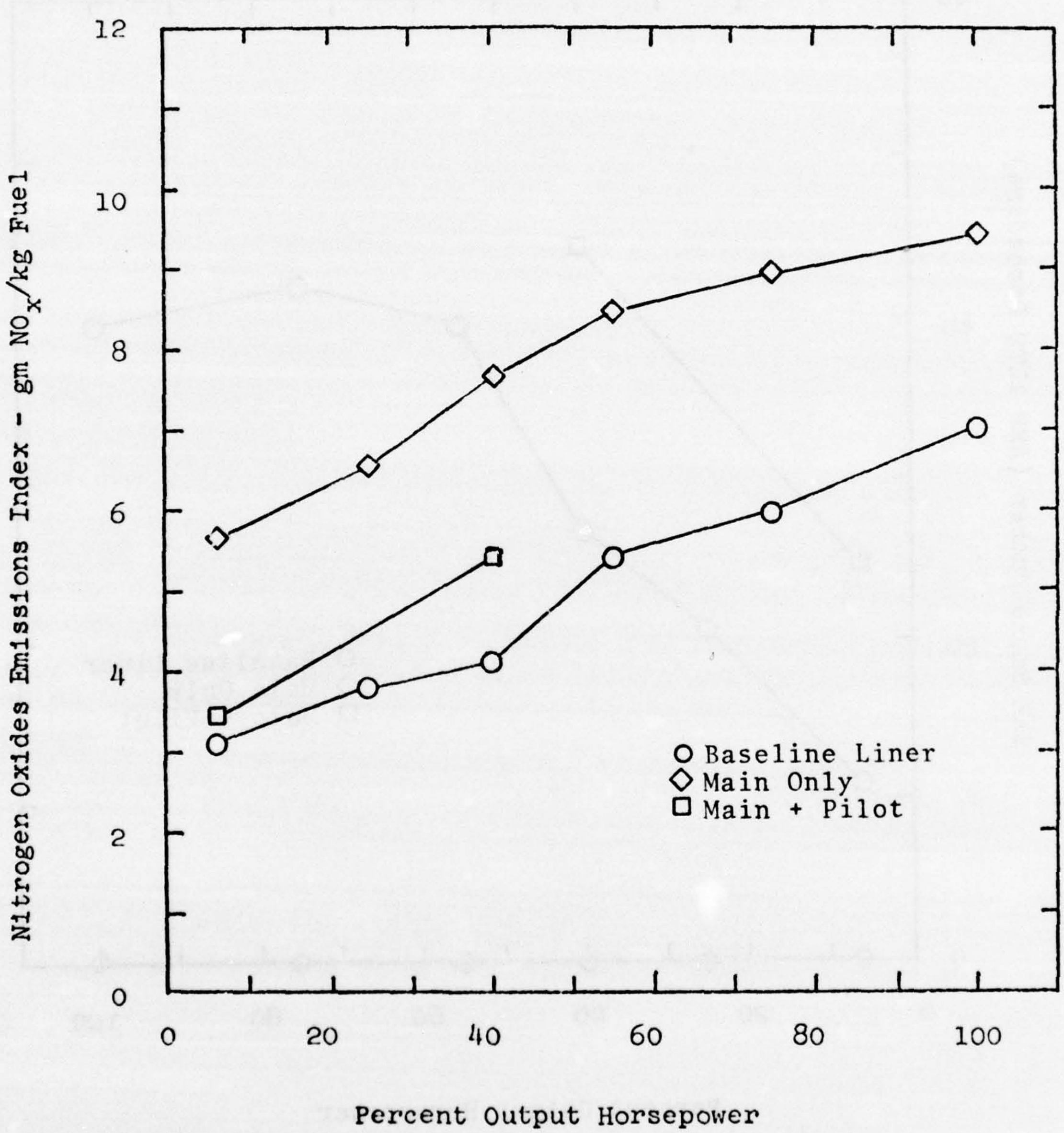

Figure 61. Prechamber Liner No. 13 and Baseline Liner Nitrogen Oxide Emissions.

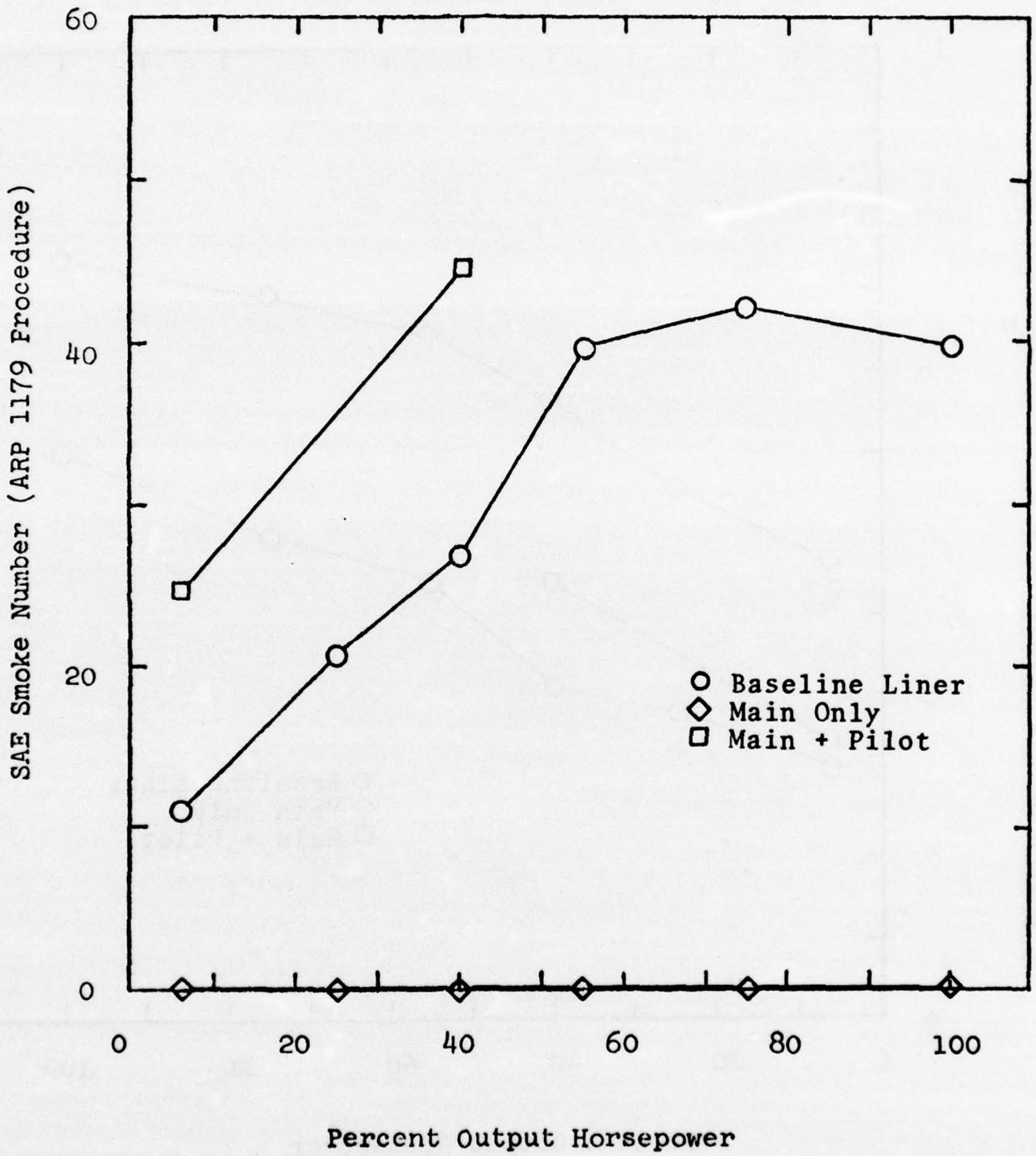

Figure 62. Prechamber Liner No. 13 and Baseline Liner Smoke Number Data.

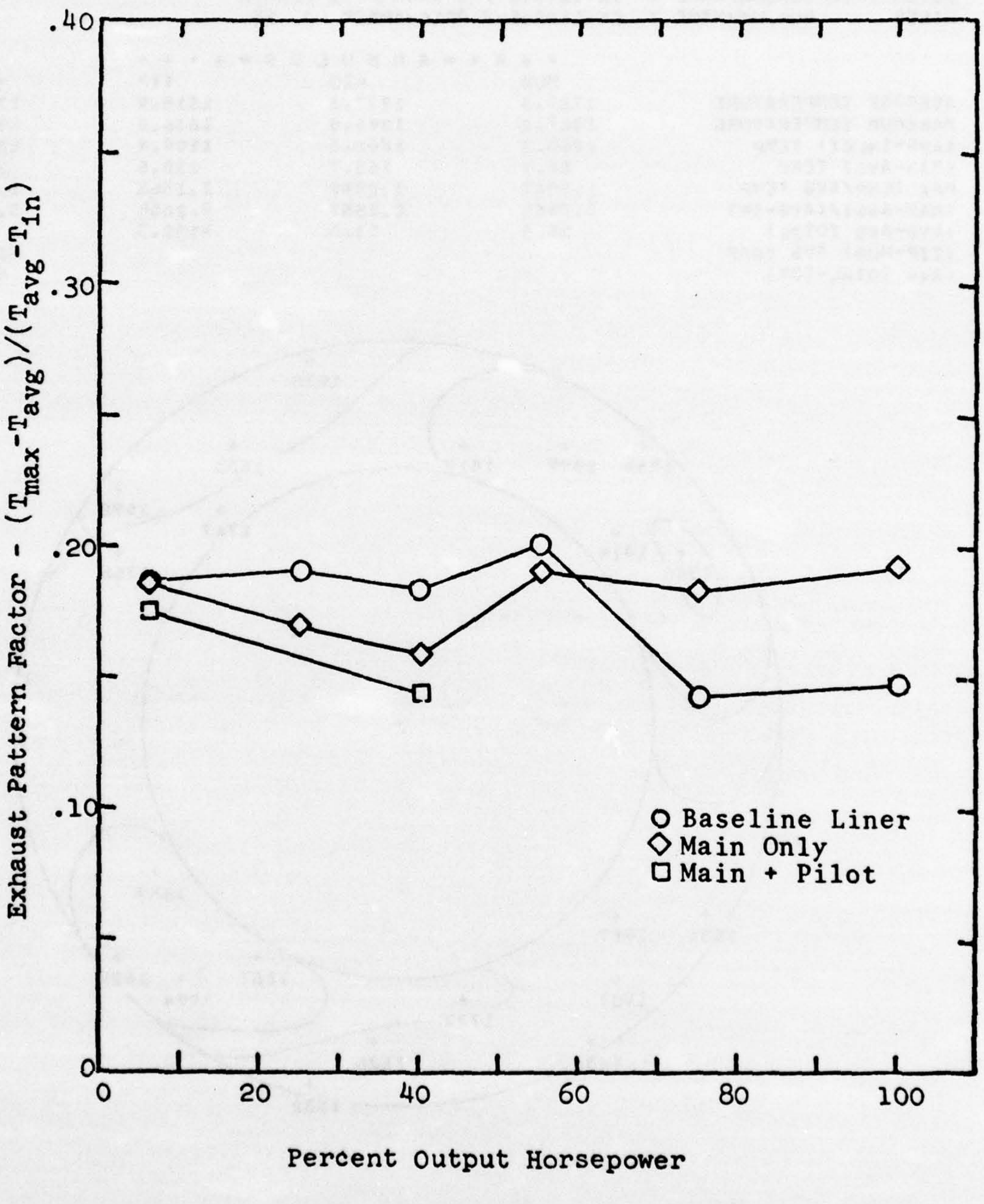

Figure 63. Prechamber Liner No. 13 and Baseline Liner Exhaust Pattern Factors.

LOW-EMISSION PRECHAMBER COMBUSTOR SYSTEM NO. 13, RIG TEST AT 75% POWER POINT
TEST DATE = 2- 6-75 READING NUMBER = 1798 INLET TEMP = 515.
ENGINE NUMBER/NAME = COMB. RIG / MODEL 250-C20B ENGINE TOT = 1255.
OUTER CASE NUMBER/NAME = EX-114012 / 3 INCH EXT. LENGTH
LINER NUMBER/NAME = EX-116291 / PRECHAMBER NO. 13

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1780.3	1777.3	1615.4	1724.3
MAXIMUM TEMPERATURE	1867.0	1946.0	1836.0	1946.0
(AVG-INLET) TEMP	1265.3	1262.3	1100.4	1209.3
(MAX-AVG) TEMP	86.7	168.7	220.6	221.7
MAX TEMP/AVG TEMP	1.0487	1.0949	1.1365	1.1286
(MAX-AVG)/(AVG-IN)	0.0685	0.1337	0.2004	0.1833
(AVG-AVG TOTAL)	56.0	53.0	-108.9	
(TIP-HUB) AVG TEMP				-164.9
(AVG TOTAL-TOT)				469.3

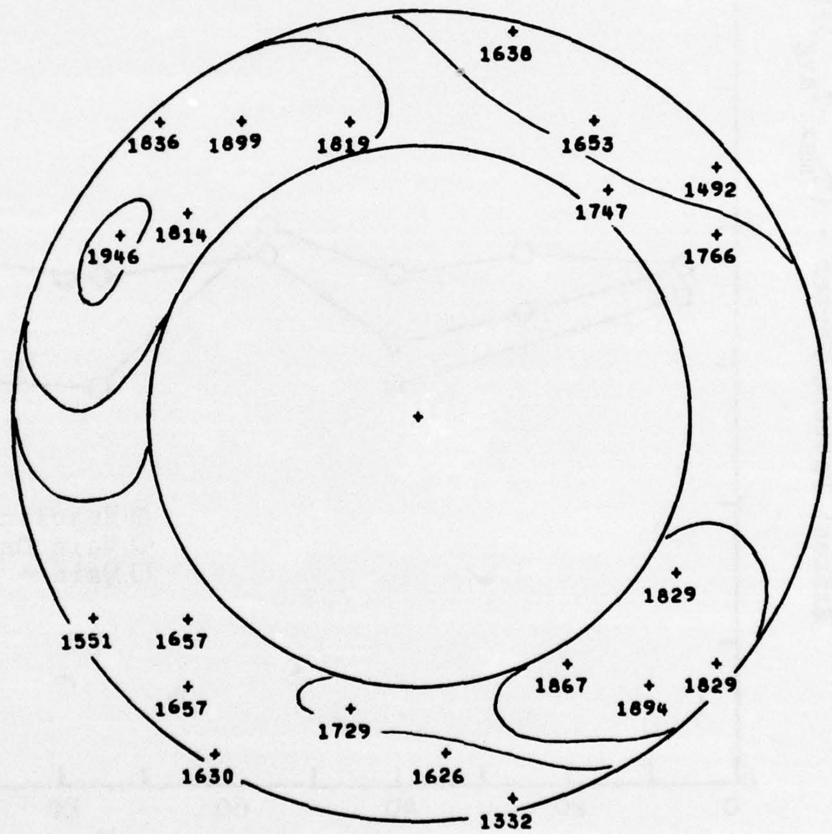

Figure 64. Prechamber Liner No. 13 Exhaust Temperatures at 75% Power.

LOW-EMISSION PRECHAMBER COMBUSTOR SYSTEM NO. 13, RIG TEST AT 100% POWER POINT
TEST DATE = 2- 6-75 READING NUMBER = 1799 INLET TEMP = 570.
ENGINE NUMBER/NAME = COMB. RIG / MODEL 250-C20B ENGINE TOT = 1490.
OUTER CASE NUMBER/NAME = EX-114012 / 3 INCH EXT. LENGTH
LINER NUMBER/NAME = EX-116291 / PRECHAMBER NO. 13

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1986.4	2001.1	1767.9	1918.5
MAXIMUM TEMPERATURE	2135.0	2178.0	2108.0	2178.0
(AVG-INLET) TEMP	1416.4	1431.1	1197.9	1348.5
(MAX-AVG) TEMP	148.6	176.9	340.1	259.5
MAX TEMP/AVG TEMP	1.0748	1.0884	1.1924	1.1353
(MAX-AVG)/(AVG-IN)	0.1049	0.1236	0.2840	0.1925
(AVG-AVG TOTAL)	68.0	82.7	-150.6	
(TIP-HUB) AVG TEMP				-218.6
(AVG TOTAL-TOT)				428.5

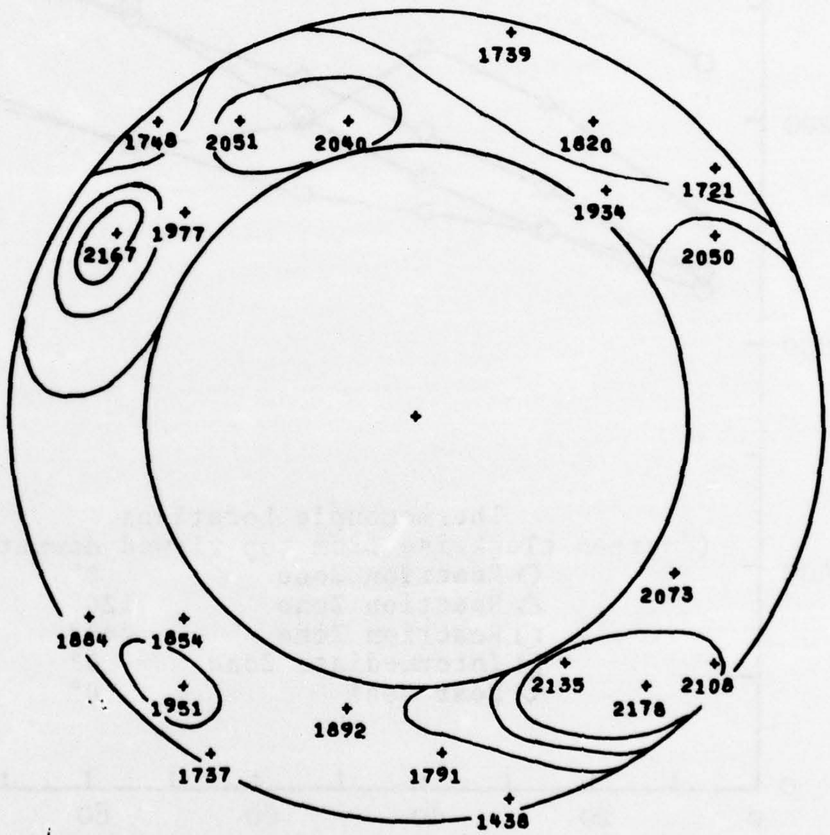

Figure 65. Prechamber Liner No. 13 Exhaust Temperatures at 100% Power.

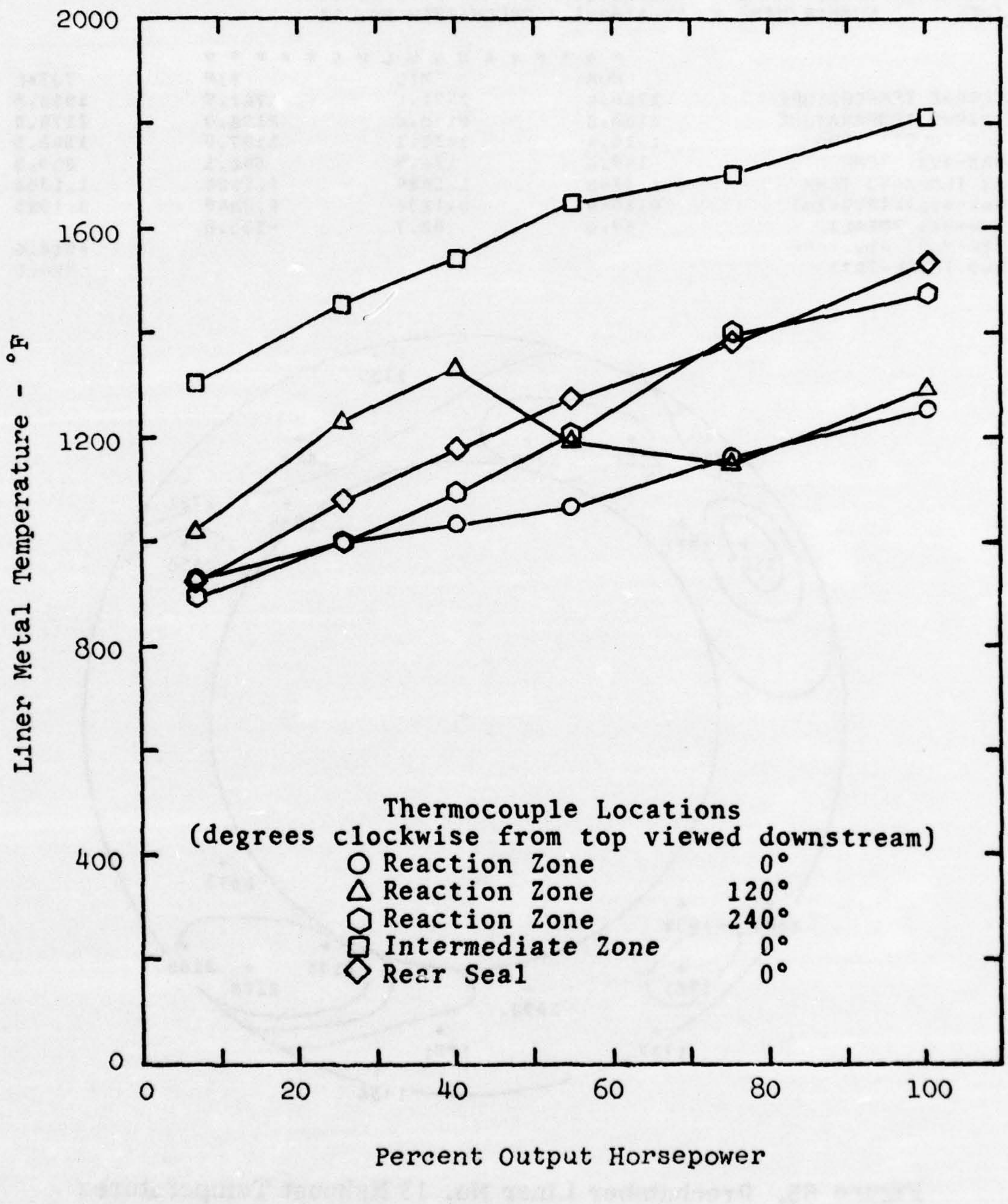

Figure 66. Prechamber Liner No. 13 Metal Temperatures, Main Only Operation.

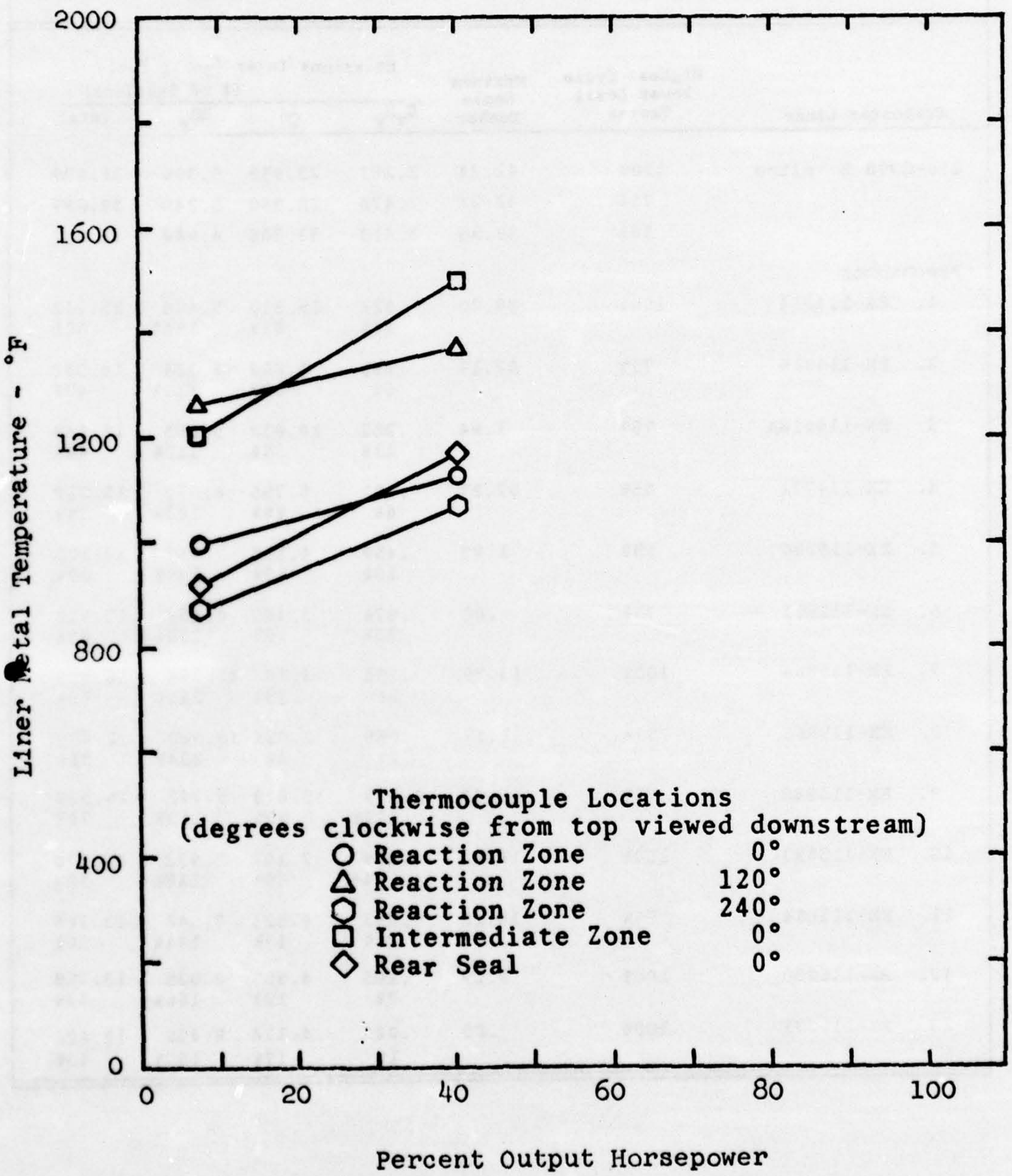

Figure 67. Prechamber Liner No. 13 Metal Temperatures, Main Plus Pilot.

TABLE 40. TIME-WEIGHTED LOH DUTY CYCLE EMISSIONS INDEX SUMMARY FOR BASELINE AND LOW EMISSIONS PRECHAMBER COMBUSTORS FROM RIG TESTS

Combuster Liner	Highest Cycle Power Level Tested	Maximum Smoke Number	Emissions Index (gm/kg Fuel) (% of Baseline) C_xH_y	CO	NO_x	Total
250-C20B Baseline	100%	42.34	2.287	23.955	5.396	31.639
	75%	42.34	2.478	25.960	5.248	33.687
	55%	39.90	3.413	33.306	4.944	41.663
Prechamber						
1. EX-114014	100%	88.70	.327 14%	19.310 81%	5.604 104%	25.242 80%
2. EX-114016	75%	52.19	.155 6%	8.202 32%	6.224 119%	14.582 43%
3. EX-114016A	75%	1.94	.282 11%	10.010 39%	5.855 112%	16.149 48%
4. EX-114771	55%	52.22	.191 6%	8.756 26%	6.070 123%	15.019 36%
5. EX-115256	55%	1.92	.459 13%	4.283 13%	7.357 149%	12.100 29%
6. EX-115861	75%	.00	.574 23%	3.485 15%	9.559 176%	13.619 43%
7. EX-115864	100%	13.79	.196 9%	3.164 13%	12.994 241%	16.355 52%
8. EX-115865	55%	1.17	.068 2%	2.826 8%	10.080 204%	12.975 31%
9. EX-115888	75%	.83	5.179 209%	15.418 59%	5.942 113%	26.539 79%
10. EX-115893	100%	14.81	.789 34%	7.107 30%	7.973 148%	15.870 50%
11. EX-115894	75%	38.22	.093 4%	4.523 17%	7.548 144%	12.166 36%
12. EX-116290	100%	2.29	.165 7%	4.657 19%	8.935 166%	13.758 43%
13. EX-116291	100%	.00	.025 1%	4.174 17%	8.426 156%	12.626 40%

TABLE 41. EXHAUST TEMPERATURE PROFILES FROM BASELINE AND LOW EMISSIONS PRECHAMBER COMBUSTORS, USING TEST RIG DATA

	Pattern Factor, $(T_m-T_a)/(T_a-T_{in})$		T_m/T_a	
Combustor Liner	75% Power	100% Power	75% Power	100% Power
Acceptable Maximum	--	.250	--	1.180
Baseline 250-C20B	.143	.148	1.101	1.106
Prechamber				
1. EX-114014	.195	.186	1.137	1.133
2. EX-114016	.356	.301	1.250	1.213
3. EX-114016A	.395	--	1.278	--
4. EX-114771	.303*	--	1.213*	--
5. EX-115256	.339	--	1.239	--
6. EX-115861	.274	--	1.197	--
7. EX-115864	.256	.250	1.183	1.178
8. EX-115865	.281*	--	1.199*	--
9. EX-115888	.354	--	1.248	--
10. EX-115893	.255	.236	1.178	1.165
11. EX-115894	.281	--	1.196	--
12. EX-116290	.220	.190	1.153	1.134
13. EX-116291	.183	.193	1.129	1.136

* 55% Power data due to high liner metal temperatures.

TABLE 42. MAXIMUM MEASURED METAL TEMPERATURES AND COMBUSTION SYSTEM PRESSURE DROPS FOR BASELINE AND LOW EMISSIONS PRECHAMBER LINERS, USING TEST RIG DATA

Combustor Liner	Maximum Metal Temperature, °F 75% Power	100% Power	Pressure Drop, % P/P 75% Power	100% Power
Acceptable Maximum	--	1700.	--	5.00
Baseline 250-C20B	1315.	1505.	3.72	3.81
Prechamber				
1. EX-114014	1611.	1760.	2.86	2.48
2. EX-114016	1726.	--	2.93	--
3. EX-114016A	1606.*	--	2.92*	--
4. EX-114771	1638.**	--	2.97**	--
5. EX-115256	1525.	--	3.80	--
6. EX-115861	1288.	--	4.27	--
7. EX-115864	1737.	1905.	4.38	4.64
8. EX-115865	1983.*	--	5.06*	--
9. EX-115888	1078.	--	3.73	--
10. EX-115893	1143.	1299.	4.11	4.13
11. EX-115894	1649.	--	3.29	--
12. EX-116290	1790.	1716.	3.71	3.64
13. EX-116291	1707.	1820.	3.95	3.85

* 40% Power conditions at standard conditions.

** 55% Power condition maximum due to high metal temperatures at higher power.

TABLE 43. COMBUSTION LINER DESIGN SUMMARY FOR DEVELOPMENT OF PRECHAMBER LINERS

Design Number	1	2	3	4	5	6	7	8	9	10	11	12	13
Prechamber Liner P/N	EX-114014	EX-114016	EX-114016A	EX-114771	EX-115256	EX-115861	EX-115864	EX-115865	EX-115888	EX-115893	EX-115894	EX-116290	EX-116291
Hole Description(No.),Dia													
Vap. Tube Exit	(36).125	(8).75x.219	(8).75x.293	(8).75x.293	-	-	-	-	(36).125	-	-	-	-
Dome Cooling	-	-	-	-	-	-	-	-	-	-	(24).125	(8).125	(8).125
Primary	-	-	-	-	(12).360	(12).360	(12).360	-	-	-	-	-	-
Primary Cooling	-	-	-	-	-	-	-	-	(48).187	(48).187	(36).125	(12).125	(12).125
Intermediate	-	-	-	-	-	-	(12).397*	(12).397*	(12).397*	(12).397*	(12).500	(12).500	(12).500
Intermediate Cooling	-	-	-	-	(48).187	(48).187	(48).187	(48).187	(48).187	(48).187	-	-	-
Dilution	(6)1.500	(6)1.358*	(6)1.312	(6)1.296*	(4)1.484*	(4)1.225*	(4)1.225*	(4)1.225*	(6).812	(6).812	(6).960*	(6).956*	(6).923*
Dilution Cooling	-	-	-	-	(72).062	(72).062	(72).062	(72).062	(72).062	(72).062	(36).125	(12).125	(12).125
Lengths													
Overall	12.170	12.060	12.060	12.060	11.920	11.920	11.920	11.920	11.920	11.920	11.920	11.920	11.920
Swirler	.434	.350	.350	.350	.350	.350	.350	.350	.350	.350	.350	.350	.350
Vaporizer Tube	4.726	3.900	3.900	3.900	2.650	2.650	2.650	2.650	2.650	2.650	1.650	1.650	1.650
Vaporizer Tube - Primary Holes	-	-	-	-	1.280	1.280	1.280	-	-	-	-	-	-
Vaporizer Tube Intermediate Holes	-	-	-	-	--	-	4.030	4.030	4.030	4.030	4.250	4.250	4.250
Primary Holes - Intermediate Holes	-	-	-	-	-	-	2.750	-	-	-	-	-	-
Primary Holes - Dilution Holes	5.150	5.040	5.040	5.040	4.930	4.930	4.930	-	-	-	-	-	-
Intermediate Holes - Dilution Holes	-	-	-	-	-	-	2.180	2.180	2.180	2.180	2.000	2.000	2.000
Dilution Holes - Rear Seal	1.600	2.540	2.540	2.540	2.540	2.540	2.540	2.540	2.540	2.540	3.500	3.500	3.500
Diameters													
Swirler OD	3.680	2.936	2.936	2.936	2.936	2.936	2.936	2.936	2.936	2.936	2.936	2.936	2.936
Swirler ID	2.410	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645
Vap. Tube ID	3.740	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Trip ID	3.480	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.900	2.900	2.900
Primary Zone ID	6.260	6.260	6.260	6.260	6.260	6.260	6.260	6.260	6.260	6.260	6.260	6.260	6.260
Intermediate Zone ID	-	-	-	-	-	-	6.260	6.260	6.260	6.260	5.640	5.640	5.640
Dilution Zone ID	5.640	5.640	5.640	5.640	5.640	5.640	5.640	5.640	5.640	5.640	5.640	5.640	5.640
Rear Seal ID	6.160	6.160	6.160	6.160	6.160	6.160	6.160	6.160	6.160	6.160	6.160	6.160	6.160

*Equivalent Diameter

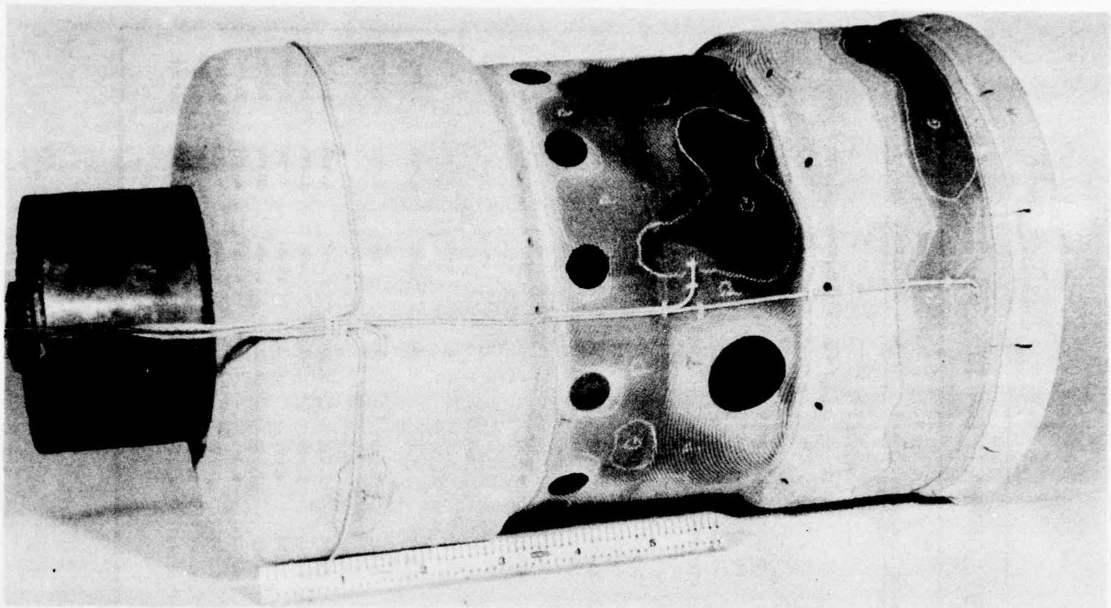

Figure 68. Prechamber Liner No. 13 Metal Temperature Pattern at 100% Power, External 300°-60° Rotation.

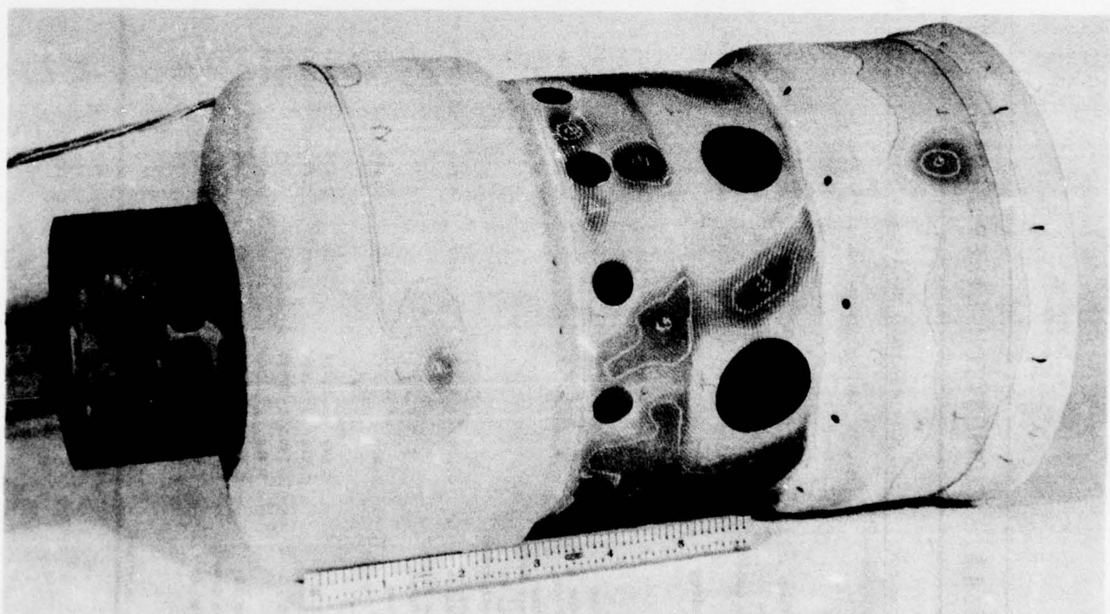

Figure 69. Prechamber Liner No. 13 Metal Temperature Pattern at 100% Power, External 60°-180° Rotation.

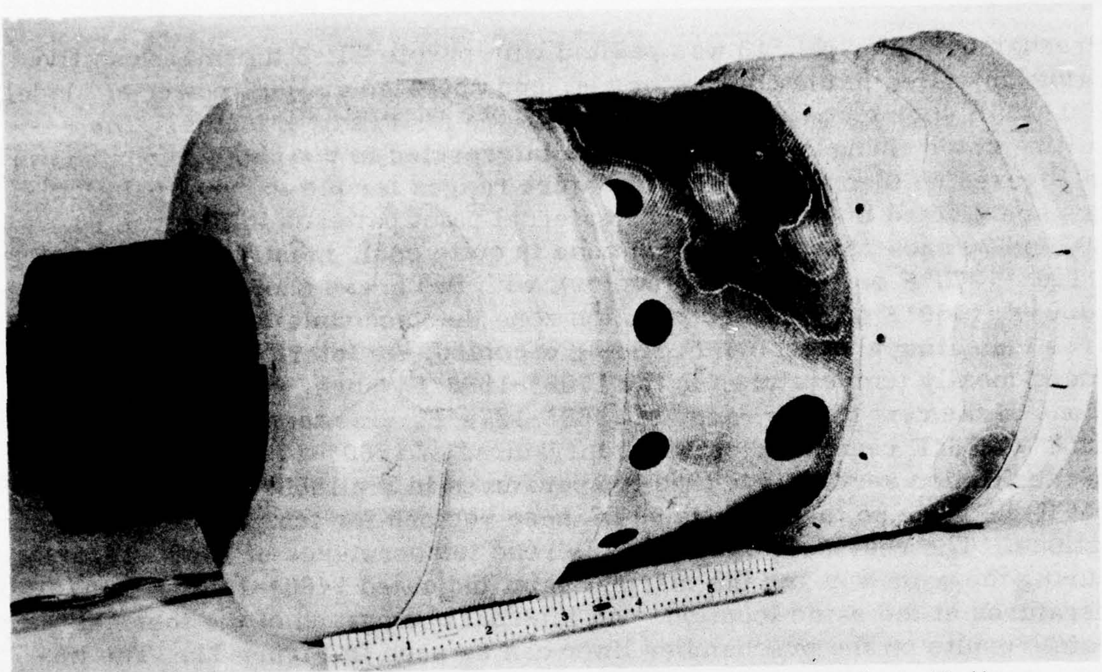

Figure 70. Prechamber Liner No. 13 Metal Temperature Pattern at 100% Power, External 180°-300° Rotation.

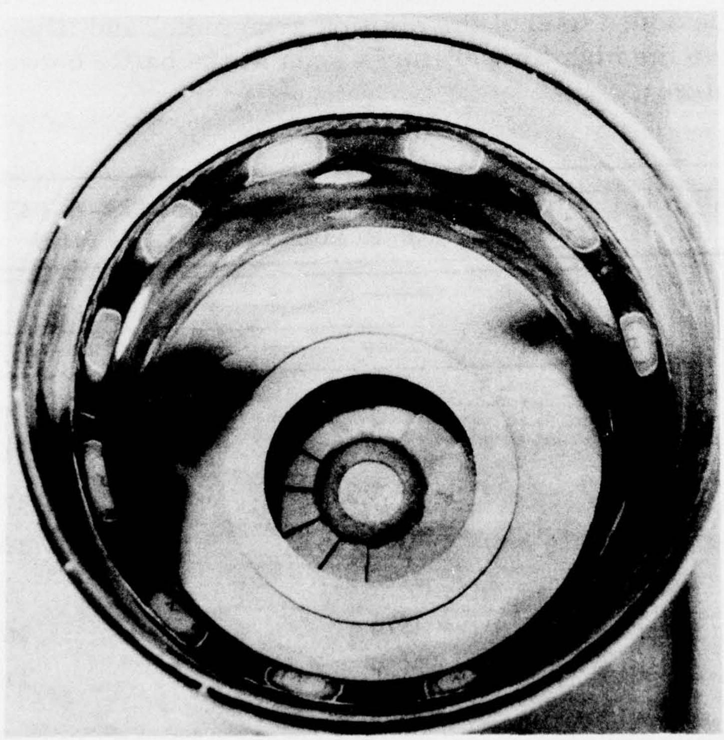

Figure 71. Prechamber Liner No. 13 Metal Temperature Pattern at 100% Power, Internal.

Prechamber liner No. 13 was painted with purple TP-6 thermal sensitive paint, installed in the combustor rig, and operated at 100% power at Model 250-C20B engine combustor inlet conditions for twenty minutes. The resulting color changes in the paint are interpreted in the photographs shown in Figures 68 through 71. Temperature ranges for the thermal paint colors are defined in Table 44. The external paint patterns in Figures 68, 69, and 70 show that the reaction zone is quite cool, mostly under 1400°F (1190°-1270°F on two thermocouples), with two areas showing 1400°-1700°F (1550°F on the third reaction zone thermocouple) and one small area indicating above 1700°F. Being uncooled, the intermediate zone produced mostly temperatures in the 1706°-1868°F range, with several regions of the next higher range of 1868°-1976°F. One thermocouple in this 1868°-1976°F region indicated temperatures of 1780°-1795°F. Two areas of the dilution section indicated temperatures in the 1868°-1976°F range, but there were no thermocouples in these regions for temperature correlations. The rear seal thermocouple read temperatures of 1600°-1615°F during the paint run and the thermal paint indicated 1400°-1706°F temperatures at the same location. An internal photograph of the thermal paint results on the prechamber liner can be seen in Figure 71. The impingement of the dilution zone film-cooling holes is very noticeable in this view. The internal thermal pattern is, as expected, similar to the external pattern with the general increases in temperature evident. More holes should be added to cool the dilution zone metal and film cooling baffle to reduce the high temperatures seen at the baffle between the exiting cooling holes.

TABLE 44. THERMALLY SENSITIVE TYPE, TP-6 PAINT TEMPERATURE RANGE INTERPRETATION

Letter	Temperature Range (°F) Over	Below
-		968
N	968	1400
T	1400	1706
P	1706	1868
G	1868	1976
M	1976	2030
Y	2030	2102
R	2102	-
\\\\\\	Paint Eroded	

The prechamber liner should be capable of engine operation although some areas do reach metal temperatures higher than the 1700°F maximum program goal. Examination of the liner revealed no local melting or thermal distortion.

Prechamber liner No. 13 also underwent ambient and simulated altitude starting tests on the combustor test rig. The standard Model 250-C20B spark-ignition system was used with the spark plug mounted approximately 1.00 inch downstream of the fuel nozzle, normal to the liner centerline, and had the plug tip flush with the inside surface of the liner vaporizer tube. The plug insertion depth was variable, but the flush setting was used throughout the test, since additional penetration was not required to achieve satisfactory starts.

Ambient inlet temperature (37-43°F) and ambient inlet pressure (14.7-15.6 psia) starting was conducted over a range of airflow rates from 0.48 to 0.94 lb/sec. Combustor pressure drops varied from 1.8 to 6.3%. Successful starts were accomplished at the conditions given in Table 45.

The inlet pressure was then reduced to approximately 5.46 psia to simulate the ambient pressure at 25,000 feet. At this condition, starts were attempted at airflow rates from 0.19 to 0.27 lb/sec. Successful starts were achieved at the 0.19 lb/sec airflow rate, as documented in Table 45.

TABLE 45. OPERATING CONDITIONS UNDER WHICH PRECHAMBER LINER NO. 13 ACHIEVED SUCCESSFUL STARTS

Airflow (lb/sec)	Inlet Press. (psia)	Inlet Temp. (°F)	Press. Drop (%)	Fuel Flow Pilot (lb/hr)	Fuel Flow Main (lb/hr)	Outlet Temp. (°F)
.479	14.69	42.	1.79	-	21.9	837.
.597	14.88	37.	2.63	-	22.2	699.
.653	15.01	37.	3.21	-	26.1	777.
.191	5.42	34.	1.18	-	19.1	901.

All of the starting was accomplished using the DDA airblast fuel injector EX-115870C with only the main airblast fuel system. For this combustor a separate pilot fuel system was not required for starting.

MODIFIED CONVENTIONAL COMBUSTOR

The modified conventional combustor design concept and the prechamber combustor design concept, discussed in the preceeding section, were developed simultaneously in the DDA Combustion Research Facility. Beginning with the technology demonstration combustor from the previous contract, this combustor also passed through a series of development configurations and combustor rig tests with the goal of achieving the acceptance criteria defined in Table 2. This combustor performance goal included a 50% reduction in the LOH duty cycle time-weighted exhaust emissions produced by the production Model 250-C20B engine combustor. It would also exhibit a good exhaust temperature profile, low pressure drop, satisfactory liner metal temperatures, stability, a lean blow-out margin, acceptable ignition, and a size compatible with engine installation.

Operating conditions for the modified conventional combustor were the LOH duty cycle conditions defined for the Model 250-C20B engine in Table 1. Low-emission features incorporated into the modified conventional were:

1. Airblast fuel injection instead of pressure-atomized fuel injection for improved fuel break-up and distribution and for more uniform and smaller fuel droplet sizes.
2. Convection cooling of the liner primary zone instead of film cooling to reduce the quenching of carbon, carbon monoxide, and unburned hydrocarbons.
3. Delayed dilution to allow more residence time at intermediate temperatures to permit the more complete oxidation of carbon, carbon monoxide, and unburned hydrocarbons, especially at low power.
4. Variable dilution geometry to permit external control of the primary zone airflow distribution and thus the local equivalence ratio and temperature to either encourage the oxidation of carbon, carbon monoxide, and unburned hydrocarbons, or suppress the oxidation of nitrogen and nitrogen compounds.

The modified conventional liner was maintained at the same overall length as the production baseline liner, 9.56 inches. The outer case was, in fact, a production outer case with two access tubes through which the liner dilution variable-geometry actuator rods passed. The ignition system used was identical to the production capacitive-discharge ignition from the Model 250-C20B production engine. The entire liner dome was from a production liner, including swirl baffles and igniter ferrule, but the fuel nozzle ferrule was replaced to accommodate the larger diameter of the airblast fuel nozzle.

Each of the modified conventional combustors tested during the development phase of the program will be discussed briefly in this section. Photographs and test data tables will be included, as well as LOH duty cycle emission summaries and percentage comparisons against baseline emissions. A set of summary tables will be presented at the end of the section, as well as thermal paint documentation of liner metal temperatures at takeoff conditions, plus rig test results of ambient and simulated altitude ignition.

During a development program the incorporation of variable geometry into a mechanical design to be used in the minimization of exhaust emissions requires significantly more data points than a fixed combustor design to assess the effectiveness of the variable geometry and the trade-offs possible over the duty cycle. Because test time is so much more expensive than analysis time, it is necessary to record enough data at different operating conditions and geometry settings so that the character of the liner can be mapped and then dealt with analytically. For the modified conventional combustor, from three to five different settings were selected prior to operating the combustor at the six or seven operating conditions in the LOH duty cycle. The particular geometry settings tested were chosen during the rig test to produce emissions data, whenever possible, on either side of the baseline emissions. These data were then plotted as shown in Figure 72. A smooth family of curves were drawn through these data to both smooth any scatter in the emissions values and to permit interpolation of emissions at geometries between those actually run. The generation of an emissions matrix which included eight or ten geometry settings minimized the possibility of missing minimum emissions combinations.

For the eventual engine testing, the control for the variable geometry actuation was a two-position system: one position for low power and one position for high power engine operation. An infinitely-variable geometry control would have resulted in slightly lower emissions, but the complexity was not warranted for this engine demonstration. Therefore, for most modified conventional combustor configurations, two LOH duty cycle emissions summaries are presented: the first using the actual data point emissions and the second using the interpolated or curve-fitted emissions for each emission type.

<u>Modified Conventional Liner No. 1</u>

This combustor is the same piece of hardware which concluded the technology demonstration testing in the previous contract.[2] A photograph of this liner appears in Figure 73. The airblast fuel nozzle, designed and

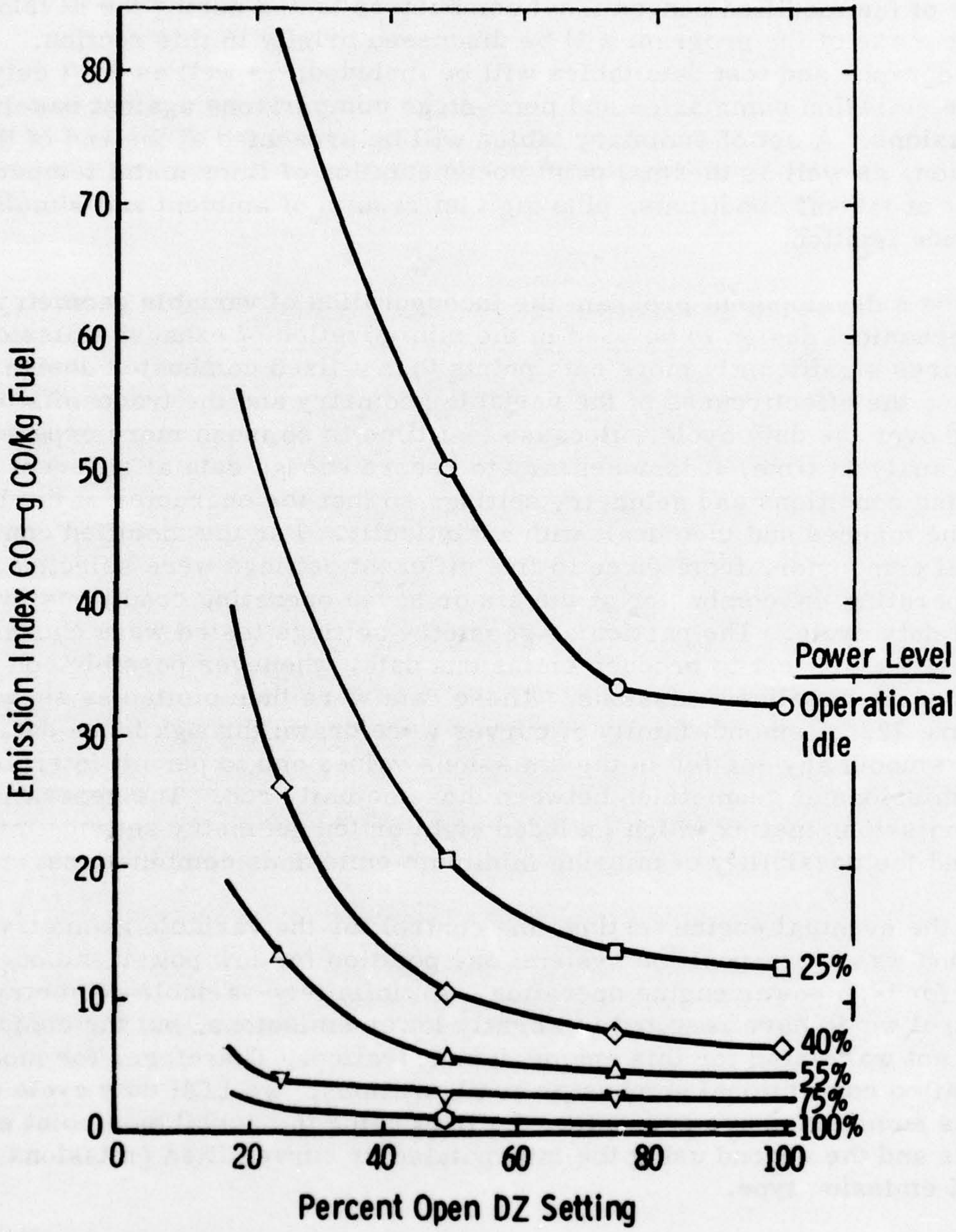

Figure 72. Typical Emissions Interpolation Curves for Modified Conventional Liner Variable Geometry Data.

Figure 73. Modified Conventional Liner No. 1, EX-114013.

fabricated by the Ex-Cell-O Corporation, used radial swirler slots which brought air past the simplex main spray tip. A separate spacer maintained adequate clearance between the nozzle and liner ferrule to assure an adequate air supply to the swirl slots. A photograph of the fuel nozzle is given in Figure 74.

Because of the lack of effectiveness experienced in the technology program at dilution settings between 72% and 100% open, only two settings were explored during this test: 50% and 75% open based on linear travel of the actuator rods. The combustor rig test results for the 75% open dilution setting are shown in Table 46 and the 50% open setting in Table 47. For the common power points, 40% and 55% power, the 50%-open geometry setting gave lower emissions and a better pattern than the more open setting.

The LOH duty cycle, time-weighted average emissions shown in Table 48 were based on emissions from 75% open geometry setting for operational idle and 25% power and from the 50% open geometry setting for all higher power levels. The percent of baseline values were computed using the second set of baseline emissions recorded after the repair of the combustor rig. If these modified conventional liner emissions were compared with the initial baseline emissions (the same rig conditions for both tests), the percentages would be 37% for CH_x, 50% for CO, 131% for NO_x, and 66% for total emissions. Based on these data, there was no trade-off possibility between CO and NO_x since both required reductions to achieve the goal of a 50% total reduction.

Modified Conventional Liner No. 2

Based on the results from the initial combustor configurations, CO reduction could be accomplished through additional intermediate zone residence time, but NO_x reduction must be attempted by suppressing the maximum flame temperatures by adding more air to the primary zone to lean the local fuel-air ratio. Also, to gain better primary zone penetration, 0.561 inch in diameter tubes were used instead of the 0.500 inch in diameter holes used on the previous configuration. For this combustor, the variable dilution geometry feature was eliminated. The variable area holes were replaced by a set of four 0.938-inch diameter holes, located 2.00 inches downstream. Photographs of this liner are presented in Figures 75 and 76.

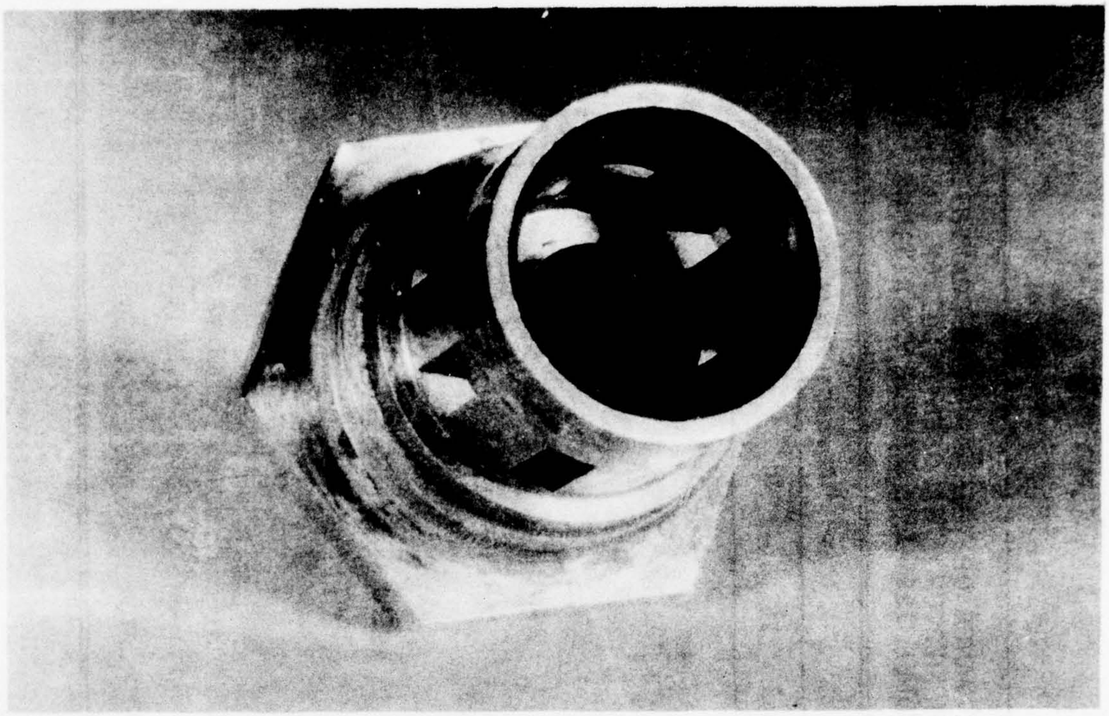

Figure 74. Ex-Cell-O Airblast Fuel Nozzle Used on Modified Conventional Liner No. 1.

To produce an improved fuel spray with smaller fuel droplets, the liner was tested with two different fuel nozzles. Both nozzles had independently controlled pilot and main supply tubes for fuel control, and both used the same body and filming-type air-blast main fuel system. The first nozzle, EX-104414, used a 2.5 flow number simplex pilot tip and the second nozzle, EX-107946, used a 3.5 flow number splash impingement pilot, as shown in Figure 77. The simplex-tip pilot nozzle developed a severe leak that terminated its testing half way through the emissions run. The second nozzle, EX-107946, performed satisfactorily. As shown in Table 49, a separate investigation of the effects of fuel flow split between pilot and main was conducted at two power points, showing that at low power, CO and NO_x concentrations can be traded by simply adjusting the pilot-main flow split. Data for a constant 20-lb/hr pilot flow are summarized in Table 50. These emissions levels were time-weight averaged over the LOH duty cycle in the top half of Table 51. If variable pilot flows were utilized, using the test data values only, the reductions in CO and total emissions illustrated in the bottom half of the table might be realized. In this combustor system, the 50% reduction in total emissions was achieved at the expense of increasing NO_x emissions.

TABLE 46. COMBUSTION SYSTEM PERFORMANCE OF THE MODIFIED CONVENTIONAL COMBUSTOR LINER, INITIAL DESIGN (75% OPEN DILUTION ZONE VARIABLE GEOMETRY) AT MODEL 250-C20B ENGINE CONDITIONS

	Idle		Percent Power				
	Ground	Operational	25	40	55	75	100
A. Emissions							
CO (ppm)		411.5	200.7	158.7	150.8		
C_3H_8 (ppm)		44.0	2.5	.3	.3		
NO_x (ppm NO_2)		29.9	38.8	48.8	57.8		
Smoke Number		20.9	29.4	32.2	39.4		
CO_2 (%)		2.35	2.75	2.80	2.95		
B. Gas Analysis							
Comb. Eff. (%)		98.58	99.62	99.71	99.74		
$F\text{-}A_{chem}/F\text{-}A_{mech}$		.988	.942	.900	.860		
C. System Performance							
Pressure Drop (%)		3.32	3.42	3.55	3.47		
T_{max}/T_{avg} (°F/°F)		1.1742	1.1880	1.2040	1.1693		
Pattern Factor		.2433	.2701	.2965	.2469		

TABLE 47. COMBUSTION SYSTEM PERFORMANCE OF THE MODIFIED CONVENTIONAL COMBUSTOR LINER, INITIAL DESIGN (50% OPEN DILUTION ZONE VARIABLE GEOMETRY) AT MODEL 250-C20B ENGINE CONDITIONS

	Idle		Percent Power				
	Ground	Operational	25	40	55	75	100
A. Emissions							
CO (ppm)				139.0	119.9	87.8	34.4
C_3H_8 (ppm)				.5	.3	.1	2.0
NO_x (ppm NO_2)				41.8	54.5	87.5	129.0
Smoke Number				16.1	22.9	27.5	25.0
CO_2 (%)				2.95	3.13	3.79	4.63
B. Gas Analysis							
Comb. Eff. (%)				99.76	99.80	99.86	99.91
$F\text{-}A_{chem}/F\text{-}A_{mech}$				.924	.911	.951	.991
C. System Performance							
Pressure Drop (%)				4.48	4.46	4.89	4.40
T_{max}/T_{avg} (°F/°F)				1.0829	1.0964	1.0962	1.1841
Pattern Factor				.1201	.1410	.1398	.2668

TABLE 48. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR MODIFIED CONVENTIONAL LINER NO. 1

MODIFIED CONVENTIONAL NO. 1. EX-114013. NOZZLE EX-CELL-O 2-POSITION 4-29-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1307.	0.15	71.43	5.820	34.575	4.123	44.518	20.90
1308.	0.00	108.06	0.275	14.025	4.460	18.760	29.36
1312.	0.15	135.17	0.048	8.921	4.406	13.375	16.09
1311.	0.45	167.06	0.028	7.174	5.356	12.558	22.90
1313.	0.20	213.26	0.010	4.565	7.476	12.051	27.52
1314.	0.05	265.59	0.141	1.535	8.839	10.515	25.00
CYCLE TOTALS		162.10	0.418	8.055	5.999	14.472	29.36
PERCENT OF BASELINE		101.28	18.27	33.63	111.16	45.74	

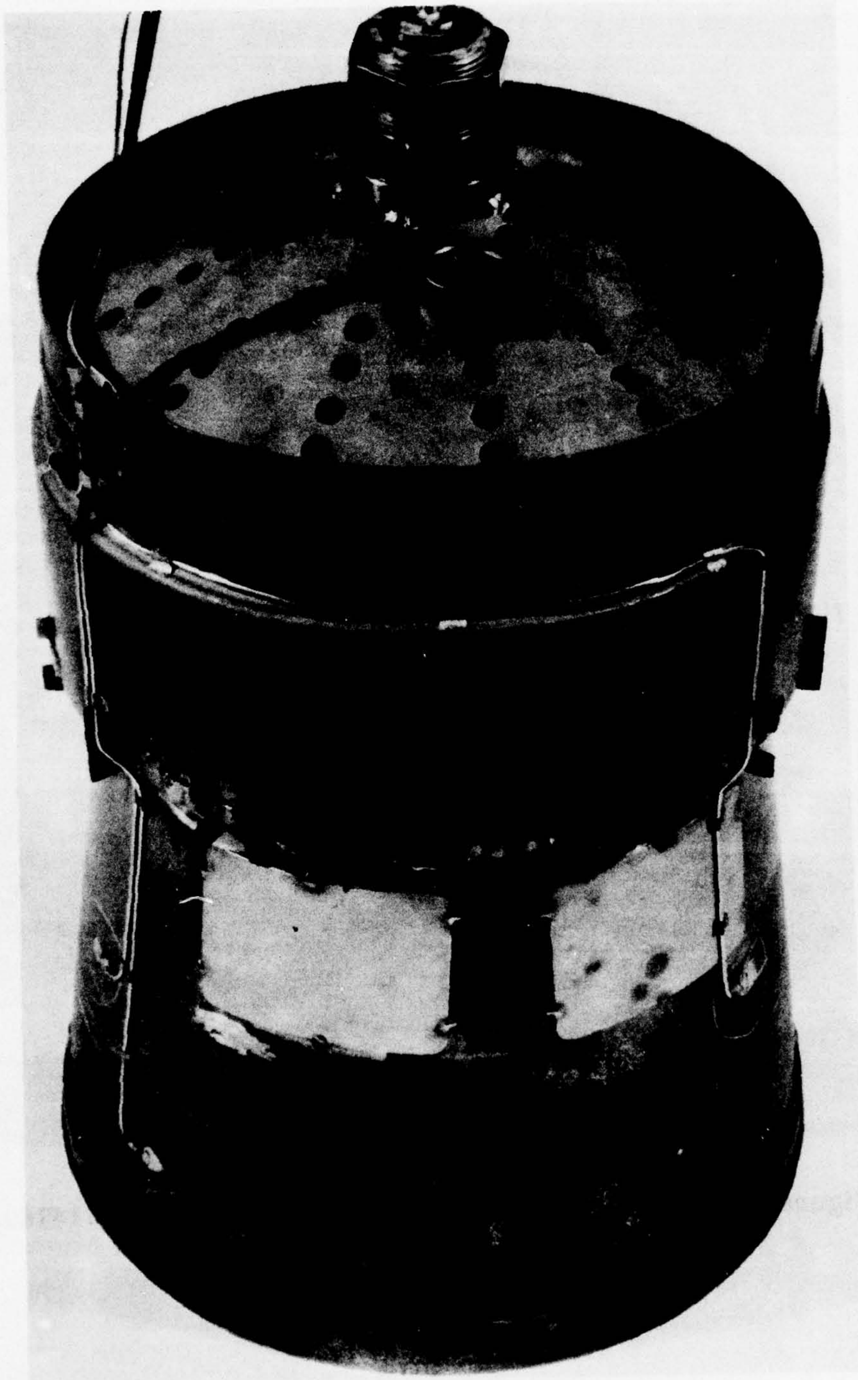

Figure 75. Modified Conventional Liner No. 2, EX-114769, External View.

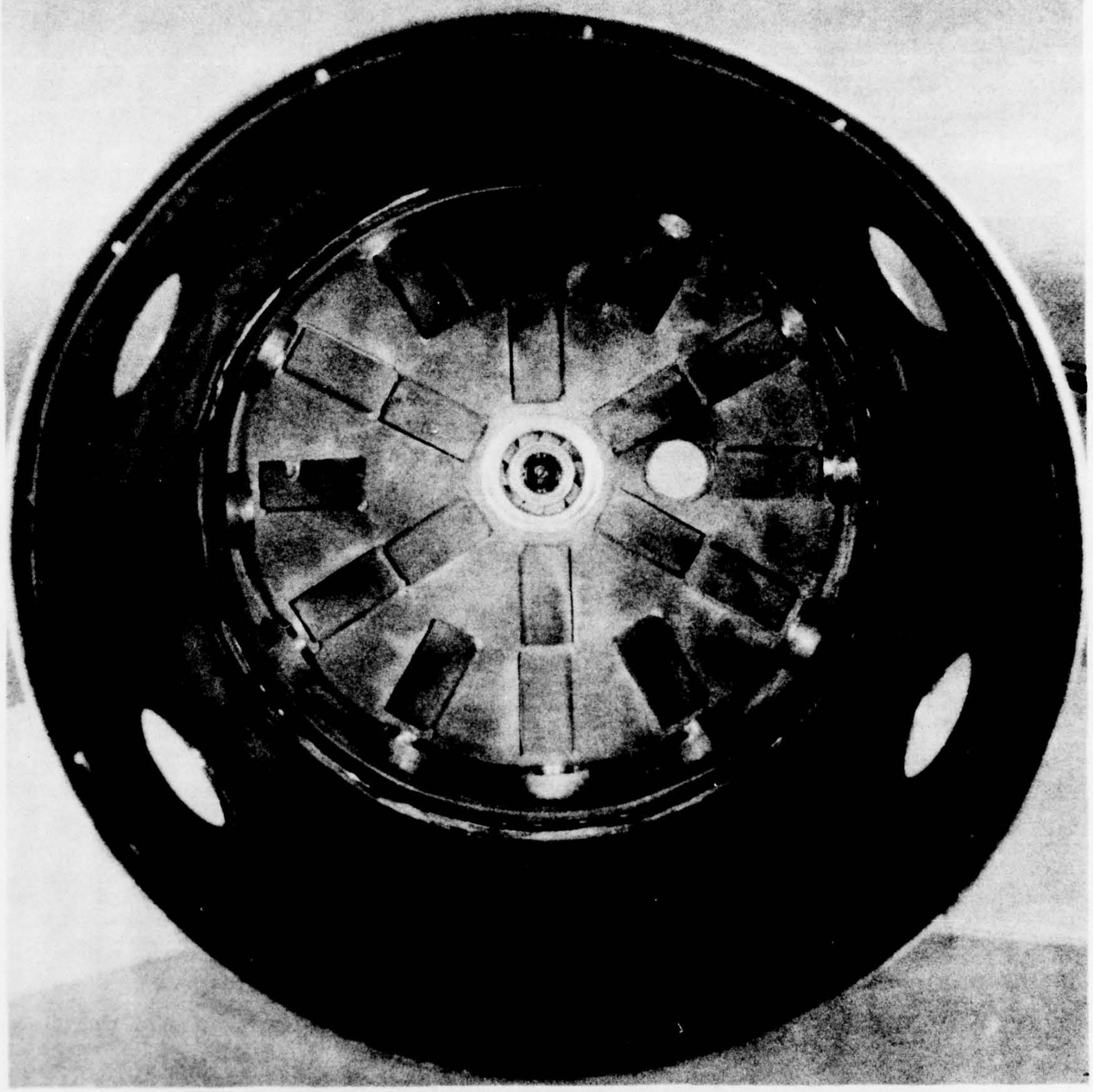

Figure 76. Modified Conventional Liner No. 2, EX-114769, Internal View.

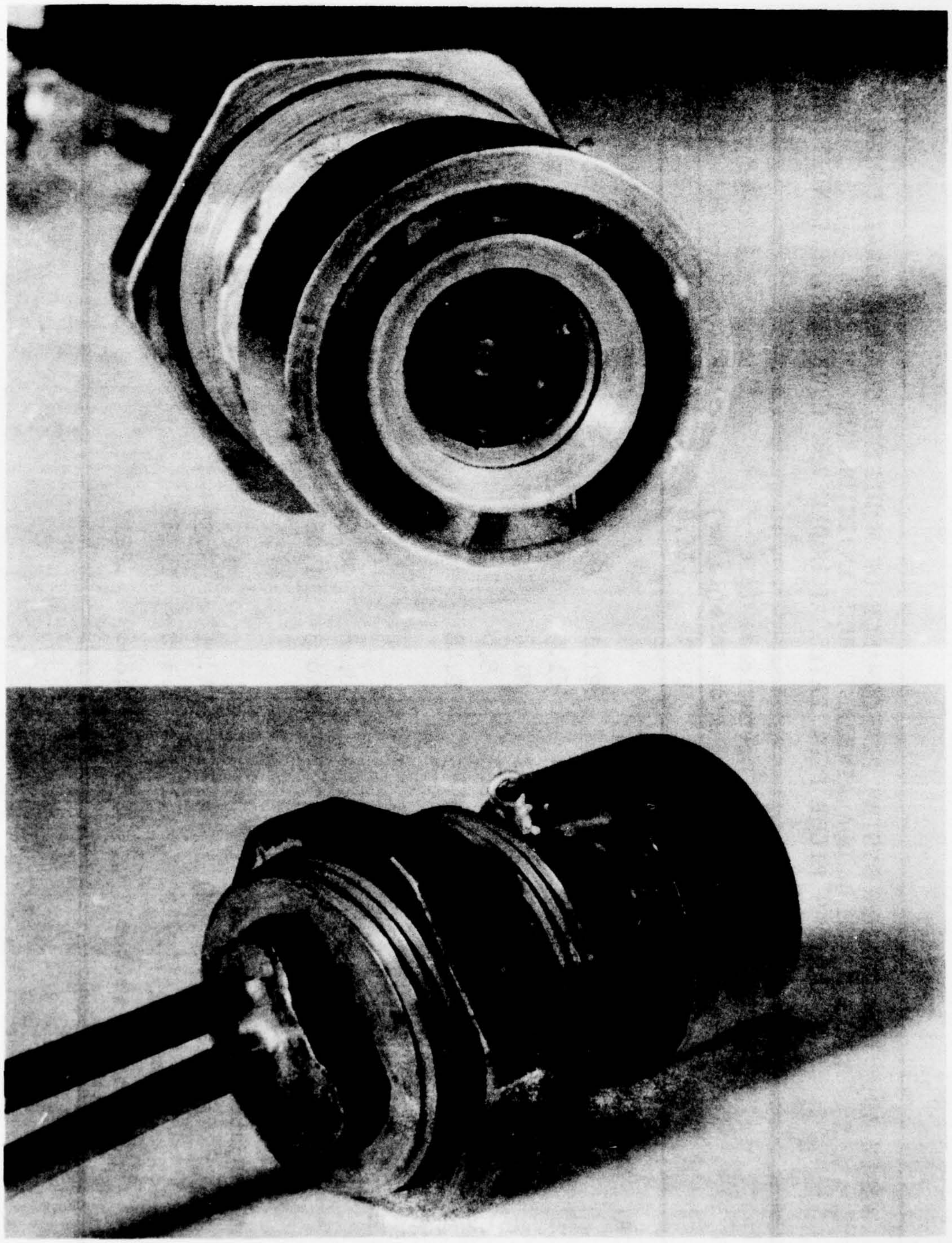

Figure 77. Airblast Fuel Nozzle EX-107946 with Splashplate Pilot.

TABLE 49. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 2 USING DDA AIRBLAST FUEL INJECTOR (EX-107946) AT VARIOUS PILOT FLOW RATES AT MODEL 250-C20B ENGINE CONDITIONS.

	Operational Idle Pilot Flow Rate(lb/hr)			55% Power Pilot Flow Rate(lb/hr)	
	0	20.1	36.8	0	20.1
A. Emissions					
CO (ppm)	929.3	821.1	651.5	89.7	90.2
C_3H_8 (ppm)	56.4	61.5	31.8	1.3	1.4
NO_x (ppm NO_2)	20.1	21.4	28.2	74.2	72.6
Smoke Number	2.8	8.0	.0	12.8	10.8
CO_2 (%)	2.45	2.48	2.50	3.52	3.60
B. Gas Analysis					
Comb. Eff. (%)	98.09	98.28	98.69	99.85	99.85
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.062	1.063	1.064	1.015	1.047
C. System Performance					
Pressure Drop (%)	4.35	4.21	4.35	4.26	4.53
T_{max}/T_{avg} (°F/°F)	1.189	1.120	1.162	1.189	1.170
Pattern Factor	.2607	.1648	.2217	.2671	.2406

TABLE 50. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 2 USING DDA AIRBLAST FUEL INJECTOR (EX-107946) AT 20 LB/HR PILOT FLOW AT MODEL 250-C20B ENGINE CONDITIONS

	Idle		Percent Power				
	Ground	Operational	25	40	55	75	100
A. Emissions							
CO (ppm)		821.1	324.4	160.7	90.2	52.4	
C_3H_8 (ppm)		61.5	6.4	2.5	1.4	2.1	
NO_x (ppm NO_2)		21.4	37.6	52.5	72.6	117.1	
Smoke Number		8.0	9.7	8.8	10.8	13.1	
CO_2 (%)		2.48	3.00	3.26	3.60	4.11	
B. Gas Analysis							
Comb. Eff. (%)		98.28	99.47	99.75	99.85	99.90	
$F\text{-}A_{chem}/F\text{-}A_{mech}$		1.063	1.047	1.047	1.047	1.024	
C. System Performance							
Pressure Drop (%)		4.21	4.18	4.43	4.53	4.83	
T_{max}/T_{avg} (°F/°F)		1.120	1.152	1.163	1.170	1.190	
Pattern Factor		.1648	.2115	.2295	.2406	.2675	

TABLE 51. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR MODIFIED CONVENTIONAL LINER NO. 2

MODIFIED CONVENTIONAL NO. 2, EX-114769, NOZZLE EX-107946, FIXED, P=20, 6-25-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1353.	0.15	69.87	8.190	69.433	2.970	80.593	8.02
1355.	0.00	106.92	0.713	23.011	4.384	28.108	9.69
1356.	0.15	134.22	0.257	10.593	5.679	16.529	8.79
1357.	0.45	165.28	0.133	5.410	7.156	12.699	10.84
1359.	0.20	215.72	0.170	2.711	9.951	12.832	13.12
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		148.13	0.731	9.858	7.473	18.062	13.12
PERCENT OF BASELINE		100.80	29.49	37.97	142.39	53.62	

MODIFIED CONVENTIONAL NO. 2, EX-114769, NOZZLE EX-107946, FIXED, P=VAR, 6-25-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1352.	0.15	69.64	4.235	55.132	3.925	63.292	0.00
1355.	0.00	106.92	0.713	23.011	4.384	28.108	9.69
1356.	0.15	134.22	0.257	10.593	5.679	16.529	8.79
1358.	0.45	166.01	0.118	5.330	7.239	12.687	12.77
1359.	0.20	215.72	0.170	2.711	9.951	12.832	13.12
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		148.43	0.442	8.788	7.582	16.812	13.12
PERCENT OF BASELINE		101.00	17.83	33.85	144.47	49.91	

Modified Conventional Liner No. 3

The modified conventional combustor No. 3, shown in Figure 78, had two design changes compared to the previous version tested.

1. The DDA airblast fuel injector, EX-107946, was replaced with a DDA airblast fuel injector, EX-114779. This was a change in pilot type only, as described below.
2. The reaction zone airflow was increased from 50% to 55% of the total flow by reducing the four fixed-geometry, dilution holes from .9375 inch in diameter to .8125 inch in diameter.

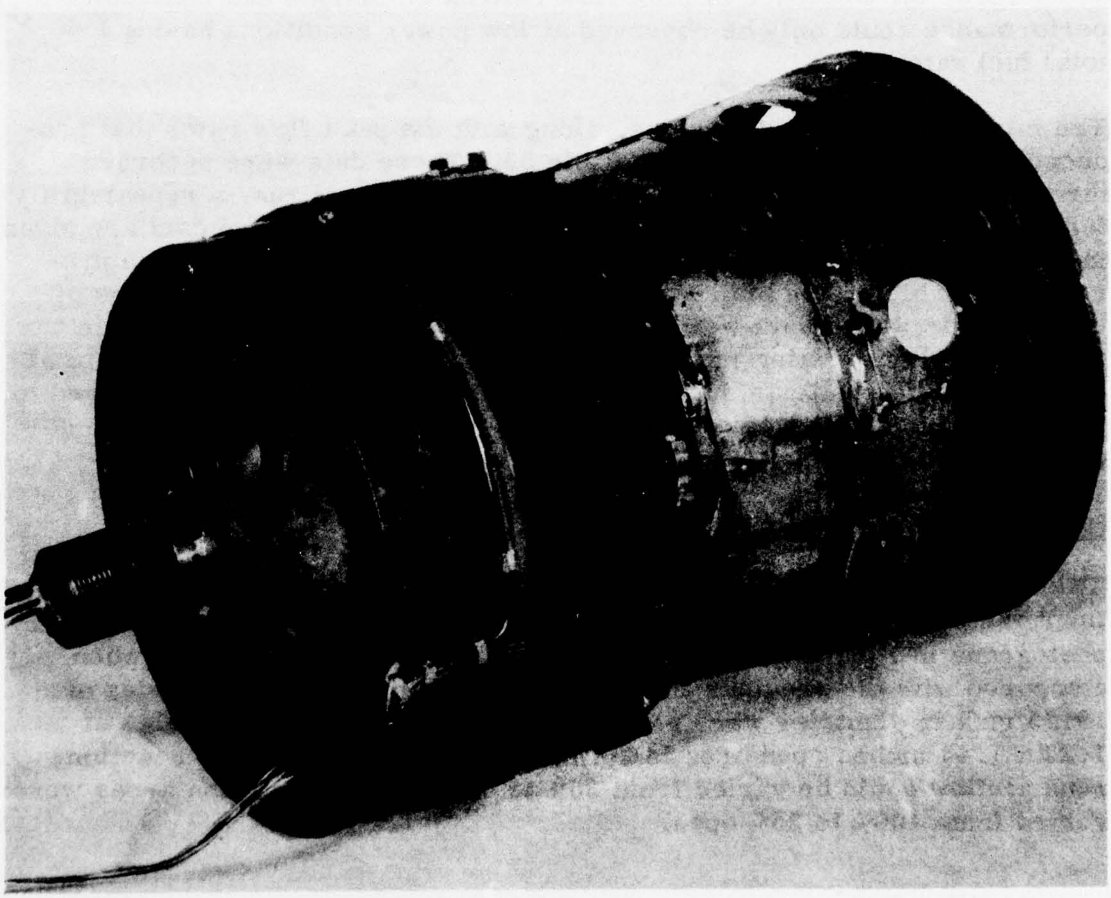

Figure 78. Modified Conventional Liner No. 3, EX-114769A.

Forcing more air through the primary reaction zone was done to reduce the flame temperature, thus suppressing NO_x formation. To counteract the resultant rise in CO and CH_x emissions at low power caused by the reduced flame temperature, the pilot to main fuel proportion from the fuel injector was externally controlled. The fuel nozzle pilot, shown in Figure 79, atomized the fuel through a 60 x 60 mesh screen, producing a narrow concentration of droplets. As recorded in Table 52, the pilot fuel rate was varied from 0 to 100% (72 lb/hr) of the fuel rate at idle and over lesser ranges as the percent power operating conditions were increased. In general, the higher the pilot flow, the more concentrated the fuel spray and the lower the exhaust concentrations of CO and CH_x, caused by higher localized flame temperatures in the primary zone. Because the pilot flow number was small, about 3.5, compared with the main fuel flow number, about 28.0, the influence of pilot flow rate on emissions and combustor performance could only be observed at low power conditions having low total fuel rates.

The minimum exhaust emissions, along with the pilot flow rates that produced them, are summarized in Table 53. These data were recorded through 75% power conditions. Subsequent to this test run, a repeatability test was conducted to include 100% power emissions. These data are given in Table 54. LOH duty cycle, time-weight averaged emissions are presented in Table 55 for the initial emissions test and for combinations of the two tests where data were added from the other test only for those conditions where testing was not conducted. For both individual and total emissions, the two tests duplicated very well. The emissions appeared to very nearly meet the goals even though there was no dilution variable geometry in this design.

Modified Conventional Liner No. 4

This modified conventional combustor was fabricated and tested to document the performance advantages of dilution-zone variable geometry. The photograph in Figure 80 reveals that the only change in this liner when compared with the previous liner is that the four fixed dilution holes of .8125 inch in diameter were replaced with four variable area holes of 1.22 x 1.40 inches open area in the same location. Thus, the reaction-zone airflow could be varied from 35% to 60% when the dilution areas were varied from 100% to 25% open.

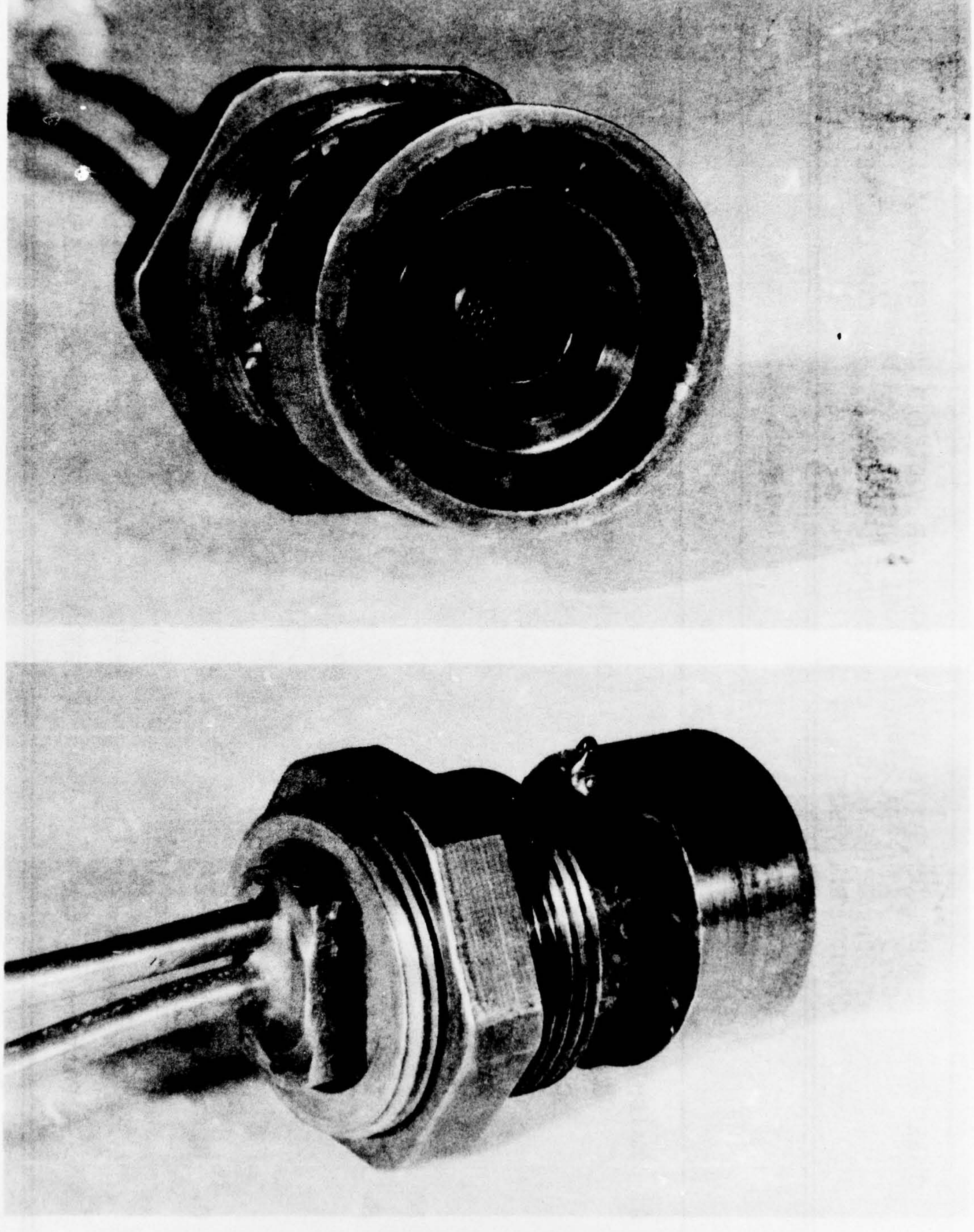

Figure 79. Airblast Fuel Nozzle EX-114779 with Screen Impingement Pilot.

TABLE 52. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 3 WITH DDA AIRBLAST FUEL NOZZLE (EX-114779) AT OPERATIONAL IDLE CONDITIONS FOR MODEL 250-C20B ENGINE CONDITIONS (PART 1 OF 3)

	Pilot Fuel Rate (lb/hr)				
	0.0	20.1	39.4	59.9	72.9
A. Emissions					
CO (ppm)	1201.4	1160.8	1004.2	856.6	786.1
C_3H_8 (ppm)	92.3	83.1	56.4	39.0	36.9
NO_x (ppm NO_2)	19.6	19.1	19.8	20.8	20.8
Smoke Number	7.1	3.7	5.3	4.3	3.1
CO_2 (%)	2.45	2.50	2.55	2.45	2.45
B. Gas Analysis					
Comb. Eff. (%)	97.50	97.65	98.04	98.29	98.42
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.051	1.074	1.086	1.035	1.031
C. System Performance					
Pressure Drop (%)	5.01	4.97	4.76	5.04	5.16
T_{max}/T_{avg} (°F/°F)	1.169	1.186	1.184	1.192	1.263
Pattern Factor	.2343	.2573	.2552	.2645	.3655

TABLE 52. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 3 WITH DDA AIRBLAST FUEL NOZZLE (EX-114779) AT OPERATIONAL IDLE CONDITIONS FOR MODEL 250-C20B ENGINE CONDITIONS (PART 2 OF 3)

	25% Power Conditions Pilot Fuel Rate (lb/hr)			40% Power Conditions Pilot Fuel Rate (lb/hr)		
	20.4	39.4	60.6	0.0	19.5	39.4
A. Emissions						
CO (ppm)	525.3	491.2	419.0	273.2	273.2	257.6
C_3H_8 (ppm)	8.4	7.7	5.4	2.5	2.8	2.5
NO_x (ppm NO_2)	30.3	30.3	31.3	39.4	40.5	41.4
Smoke Number	7.5	9.3	7.6	8.0	7.8	8.3
CO_2 (%)	2.85	2.90	2.90	3.16	3.21	3.16
B. Gas Analysis						
Comb. Eff. (%)	99.13	99.19	99.31	99.58	99.59	99.60
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.011	1.021	1.028	1.025	1.026	1.013
C. System Performance						
Pressure Drop (%)	4.50	5.06	4.74	4.95	4.90	5.09
T_{max}/T_{avg} (°F/°F)	1.131	1.160	1.145	1.145	1.129	1.140
Pattern Factor	.1851	.2242	.2041	.2066	.1838	.1996

TABLE 52. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 3 WITH DDA AIRBLAST FUEL NOZZLE (EX-114779) AT OPERATIONAL IDLE CONDITIONS FOR MODEL 250-C20B ENGINE CONDITIONS (PART 3 OF 3)

	55% Power Conditions Pilot Fuel Rate (lb/hr)		75% Power Conditions Pilot Fuel Rate (lb/hr)
	0.0	20.1	0.0
A. Emissions			
CO (ppm)	154.7	154.7	74.6
C_3H_8 (ppm)	1.6	1.7	1.5
NO_x (ppm NO_2)	51.7	52.7	75.6
Smoke Number	8.4	8.9	9.7
CO_2 (%)	3.47	3.50	4.00
B. Gas Analysis			
Comb. Eff. (%)	99.77	99.77	99.88
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.019	1.027	1.011
C. System Performance			
Pressure Drop (%)	5.11	4.99	5.08
T_{max}/T_{avg} (°F/°F)	1.142	1.154	1.149
Pattern Factor	.2034	.2201	.2123

TABLE 53. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 3 WITH DDA AIRBLAST FUEL NOZZLE (EX-114779) AT MINIMUM EMISSIONS PILOT FUEL RATES AT MODEL 250-C20B ENGINE CONDITIONS

	Opr'l.	Percent Power			
	Idle	25	40	55	75
Pilot Flow Rate (lb/hr)	72.9	60.6	39.4	20.1	0
A. Emissions					
CO (ppm)	786.1	419.0	257.6	154.7	74.6
C_3H_8 (ppm)	36.9	5.4	2.5	1.7	1.5
NO_x (ppm NO_2)	20.8	31.3	41.4	52.7	75.6
Smoke Number	3.1	7.6	8.3	8.9	9.7
CO_2 (%)	2.45	2.90	3.16	3.50	4.00
B. Gas Analysis					
Comb. Eff. (%)	98.42	99.31	99.60	99.77	99.88
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.031	1.028	1.013	1.027	1.011
C. System Performance					
Pressure Drop (%)	5.16	4.74	5.09	4.99	5.08
T_{max}/T_{avg} (°F/°F)	1.263	1.145	1.140	1.154	1.149
Pattern Factor	.3655	.2041	.1996	.2201	.2123

TABLE 54. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 3 WITH DDA AIRBLAST FUEL NOZZLE (EX-114779) REPEATABILITY TEST AT MODEL 250-C20B ENGINE CONDITIONS

	Idle		Percent Power				
	Grd.	Opr'l	25	40	55	75	100
Pilot Flow Rate (lb/hr)	62.1	71.6	60.3	40.0	19.5		5.9
A. Emissions							
CO (ppm)	1081.4	717.8	411.5	252.5	154.7		40.1
C_3H_8 (ppm)	85.0	37.9	11.3	6.2	4.7		5.9
NO_x (ppm NO_2)	17.5	21.6	32.3	41.4	51.7		107.3
Smoke Number	.0	3.1	5.1	12.3	17.2		18.3
CO_2 (%)	2.30	2.48	2.90	3.16	3.50		4.61
B. Gas Analysis							
Comb. Eff. (%)	97.59	98.54	99.30	99.60	99.76		99.91
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.031	1.044	1.035	1.007	1.028		.991
C. System Performance							
Pressure Drop (%)	5.10	4.60	4.95	4.89	4.89		5.15
T_{max}/T_{avg} (°F/°F)	1.250	1.245	1.161	1.162	1.199		1.192
Pattern Factor	.3494	.3427	.2295	.2334	.2871		.2742

TABLE 55. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR MODIFIED CONVENTIONAL LINER NO. 3 (EX-114769A).

MODIFIED CONVENTIONAL NO. 3, EX-114769A,NOZZLE EX-114779, FIXED 7-2-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1388.	0.15	72.88	4.827	65.321	2.844	72.992	3.11
1391.	0.00	105.45	0.604	30.058	3.691	34.353	7.57
1394.	0.15	135.37	0.256	16.897	4.465	21.618	8.27
1395.	0.45	162.83	0.158	9.359	5.234	14.751	8.93
1397.	0.20	215.88	0.124	3.910	6.503	10.537	9.68
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		147.69	0.507	12.945	5.322	18.774	9.68
PERCENT OF BASELINE		100.50	20.47	49.86	101.41	55.73	

MODIFIED CONVENTIONAL NO. 3, EX-114769A,NOZZLE EX-114779, FIXED 7-2-74 + 8-1-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1427.	0.00	62.11	11.586	93.645	2.485	107.716	0.02
1388.	0.15	72.88	4.827	65.321	2.844	72.992	3.11
1391.	0.00	105.45	0.604	30.058	3.691	34.353	7.57
1394.	0.15	135.37	0.256	16.897	4.465	21.618	8.27
1395.	0.45	162.83	0.158	9.359	5.234	14.751	8.93
1397.	0.20	215.88	0.124	3.910	6.503	10.537	9.68
1432.	0.05	265.30	0.414	1.802	7.913	10.129	18.29
CYCLE TOTALS		160.95	0.499	12.026	5.536	18.062	18.29
PERCENT OF BASELINE		100.56	21.84	50.20	102.58	57.09	

MODIFIED CONVENTIONAL NO. 3, EX-114769A,NOZZLE EX-114779, FIXED 8-1-74 + 7-2-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1427.	0.00	62.11	11.586	93.645	2.485	107.716	0.02
1428.	0.15	71.56	4.994	60.026	2.696	67.716	3.13
1429.	0.00	107.18	1.287	29.717	3.834	34.838	5.14
1430.	0.15	135.80	0.636	16.469	4.440	21.545	12.29
1431.	0.45	162.75	0.443	9.360	5.134	14.937	17.17
1397.	0.20	215.88	0.124	3.910	6.503	10.537	9.68
1432.	0.05	265.30	0.414	1.802	7.913	10.129	18.29
CYCLE TOTALS		160.78	0.683	11.556	5.480	17.720	18.29
PERCENT OF BASELINE		100.45	29.87	48.24	101.55	56.00	

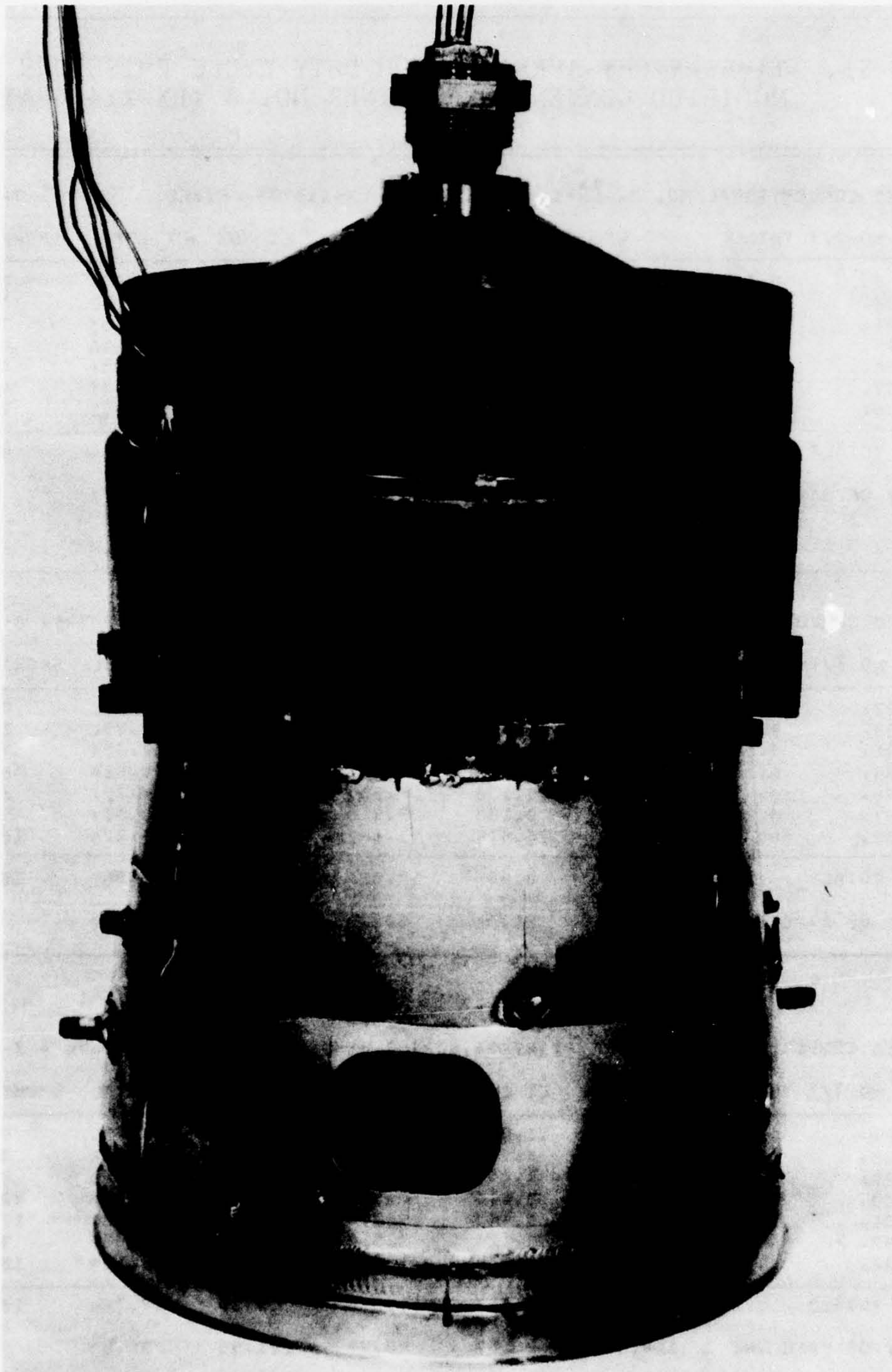

Figure 80. Modified Conventional Liner No. 4, EX-114770.

Exhaust emissions and combustor performance from the rig test are summarized in Table 56 for the four dilution area settings used: 100, 75, 50 and 25% open areas. Using the actual emissions data through 75% power, the minimum exhaust emissions with low NO_x levels over the LOH duty cycle were obtained with dilution settings of 100% open at idle, and the 50% open dilution setting from 25% - 75% power. Plotting the actual data, interpolating additional dilution settings, and extrapolating emissions to 100% power showed that 50% of baseline total emissions could be achieved with a 100% baseline NO_x if the geometry were set to 65% open from idle through 55% power and at 30% open above 55% power. These emissions results over the LOH duty cycle for both the actual and interpolated dilution settings are presented in Table 57.

The conclusions from this test were that to achieve the 50% total emissions reduction goal, a minimum of two dilution areas must be used within the constraint of no increase in NO_x emissions above baseline levels. The 50% total reduction in mass emissions plus a 10% reduction in NO_x could not be simultaneously achieved with this type of configuration. All performance parameters appear quite good, but the pressure drop was above the 5% goal.

Therefore, the next modified conventional liner had larger area primary air tubes to allow the geometry to be opened fully at idle and low power to maintain satisfactory emissions levels while lowering the combustor pressure drop.

Modified Conventional Liner No. 5

This modified conventional liner, shown in Figure 81, was reworked to have a set of larger diameter primary holes to lean the primary zone and permit dilution hole areas to be more open to reduce combustor pressure drop. The primary holes were increased from .561 inch to .750 inch in diameter. To feed these holes, a set of .500 inch holes was added through the convection cooling shroud.

A summary of the test data recorded for this combustor is presented in Table 58. It is clear from the test data that the combustor was over-leaned in the design change since very small CO and CH_x reduction was possible. Variable geometry emissions over the LOH duty cycle are presented for actual data at a 100%-open dilution geometry for up to 55% power and a 50%-open dilution setting above 55% power. Using the interpolated data set generated from the actual test data, settings of 100% open at low power through 55% power and 25% open above 55% power gave the minimum total emissions while holding NO_x to baseline levels. The over-lean primary zone resulted in less than 7% reduction in total emissions, as seen in Table 59.

TABLE 56. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 4 HAVING VARIABLE DILUTION GEOMETRY AND USING DDA AIRBLAST FUEL NOZZLE EX-114779 WITH SCHEDULED PILOT FLOWS AT 250-C20B ENGINE CONDITIONS.

	Percent Power					
	Opr'l Idle	25	40	55	75	100
Pilot Flow Rate (lb/hr)	70.	60.	40.	20.	20.	10.
I. 100% Dilution Hole Area						
A. Emissions						
CO (ppm)	318.4		116.1			
C_3H_8 (ppm)	10.3		1.3			
NO_x (ppm NO_2)	22.7		63.6			
Smoke Number	9.9		25.8			
CO_2 (%)	2.65		3.26			
B. Gas Analysis						
Comb. Eff. (%)	99.40		99.81			
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.116		1.031			
C. System Performance						
Pressure Drop (%)	4.18		4.14			
T_{max}/T_{avg} (°F/°F)	1.165		1.144			
Pattern Factor	.2263		.2021			
II. 75% Dilution Hole Area						
A. Emissions						
CO (ppm)	397.0	218.7	150.8	112.4		
C_3H_8 (ppm)	15.2	6.2	3.2	2.1		
NO_x (ppm NO_2)	18.9	37.5	50.7	61.4		
Smoke Number	9.0	16.8	22.5	24.4		
CO_2 (%)	2.45	2.95	3.26	3.57		
B. Gas Analysis						
Comb. Eff. (%)	99.19	99.62	99.76	99.83		
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.056	1.032	1.041	1.042		
C. System Performance						
Pressure Drop (%)	4.41	4.38	4.90	5.09		
T_{max}/T_{avg} (°F/°F)	1.162	1.164	1.122	1.128		
Pattern Factor	.2241	.2298	.1729	.1834		
III. 50% Dilution Hole Area						
A. Emissions						
CO (ppm)	717.8	382.9	262.7	191.9	64.1	
C_3H_8 (ppm)	30.8	7.2	3.0	2.4	1.7	
NO_x (ppm NO_2)	18.1	28.8	37.1	48.7	82.5	
Smoke Number	8.4	20.0	19.8	21.9	22.7	
CO_2 (%)	2.60	3.16	3.42	3.68	4.33	
B. Gas Analysis						
Comb. Eff. (%)	98.64	99.41	99.62	99.73	99.90	
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.119	1.112	1.083	1.094	1.089	
C. System Performance						
Pressure Drop (%)	5.04	5.06	5.43	5.82	6.01	
T_{max}/T_{avg} (°F/°F)	1.153	1.093	1.110	1.094	1.108	
Pattern Facotr	.2120	.1296	.1558	.1334	.1516	
IV. 25% Dilution Hole Area						
A. Emissions						
CO (ppm)			619.2	449.9	166.8	
C_3H_8 (ppm)			7.8	4.3	8.4	
NO_x (ppm NO_2)			31.5	38.1	59.3	
Smoke Number			6.8	6.0	10.1	
CO_2 (%)			3.26	3.44	4.00	
B. Gas Analysis						
Comb. Eff. (%)			99.10	99.38	99.77	
$F\text{-}A_{chem}/F\text{-}A_{mech}$			1.055	1.028	1.033	
C. System Performance						
Pressure Drop (%)			7.93	8.29	8.94	
T_{max}/T_{avg} (°F/°F)			1.111	1.152	1.136	
Pattern Factor			.1602	.2209	.1957	

TABLE 57. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 4 HAVING VARIABLE DILUTION GEOMETRY AND USING DDA AIRBLAST FUEL NOZZLE (EX-114779) WITH SCHEDULED PILOT FLOWS AT MODEL 250-C20B ENGINE CONDITIONS

MODIFIED CONVENTIONAL NO. 4, EX-114770, NOZZLE EX-1147 9, 2-POSITION ACT 8-7-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1448.	0.15	69.50	1.376	27.115	3.181	31.672	9.94
1453.	0.00	105.33	0.814	27.409	3.385	31.608	20.00
1457.	0.15	136.78	0.307	17.057	3.956	21.320	19.84
1460.	0.45	161.64	0.230	11.742	4.892	16.864	21.94
1462.	0.20	210.20	0.137	3.351	7.082	10.570	22.74
0.	0.05	0.00	0.000	0.000	0.000	0.000	0.00
CYCLE TOTALS		145.72	0.296	11.169	5.270	16.735	22.74
PERCENT OF BASELINE		99.16	11.94	43.02	100.40	49.68	

MODIFIED CONVENTIONAL NO. 4, EX-114770, NOZZLE EX-114779, 2-POSITION INT 8-7-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.15	69.35	2.570	41.600	2.595	46.765	0.00
0.	0.00	105.00	0.730	19.100	3.955	23.785	0.00
0.	0.15	136.50	C.230	11.600	4.565	16.395	0.00
0.	0.45	162.00	0.180	7.700	5.495	13.375	0.00
0.	0.20	210.00	0.250	7.400	5.530	13.180	0.00
0.	0.05	265.00	0.120	3.500	7.900	11.520	0.00
CYCLE TOTALS		159.03	0.356	9.990	5.395	15.742	0.00
PERCENT OF BASELINE		99.36	15.58	41.70	99.97	49.75	

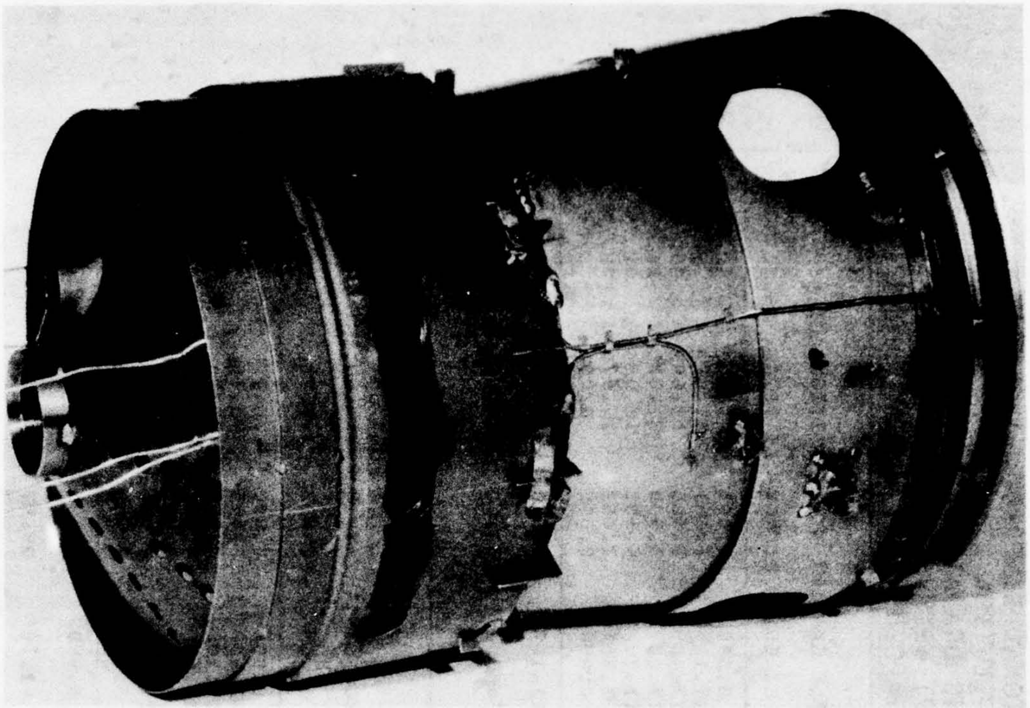

Figure 81. Modified Conventional Liner No. 5, EX-115257.

Modified Conventional Liner No. 6

The change producing this version of the modified conventional concept was a reduction in the diameter of the primary holes from the .750-inch size of liner No. 5 to a diameter of .652 inch. All other parts of the liner remained the same except for the addition of a small row of 0.125-inch diameter holes behind the primary hole tubes to discourage flameholding. An external view of this liner configuration is presented in Figure 82.

A summary of the test data recorded from this liner is given in Table 60 for the same set of four dilution hole settings as were used on the previous modified conventional liner. Unburned hydrocarbons and smoke were reduced significantly, while carbon monoxide showed some reduction and nitrogen oxides a slight increase, as expected from the richer primary zone.

LOH duty cycle emissions, employing the actual and the interpolated data, used 50% open dilution settings from idle through 55% power condition and the 25% open setting at 75% and 100% power. In each case, as seen in Table 61, NO_x emissions were kept below baseline levels, but with this constraint, CO and CH_x could not be reduced enough to achieve the 50% overall reduction in emissions.

TABLE 58. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 5 HAVING VARIABLE DILUTION GEOMETRY AND USING DDA AIRBLAST FUEL NOZZLE (EX-114779) WITH SCHEDULED PILOT FLOWS AT MODEL 250-C20B ENGINE CONDITIONS

	Opr'l Idle	Percent Power 25	40	55	75	100
Pilot Flow Rate (lb/hr)	70.	60.	40.	20.	20.	10.
I. 100% Dilution Hole Area						
A. Emissions						
CO (ppm)	751.7	587.4	435.9	211.8		
C_3H_8 (ppm)	164.5	38.3	14.9	5.0		
NO_x (ppm NO_2)	26.3	34.7	43.8	60.8		
Smoke Number	17.6	36.2	41.6	41.1		
CO_2 (%)	2.78	3.42	3.68	4.16		
B. Gas Analysis						
Comb. Eff. (%)	98.22	99.04	99.40	99.73		
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.174	1.196	1.161	1.201		
C. System Performance						
Pressure Drop (%)	2.65	2.73	2.96	3.02		
T_{max}/T_{avg} (°F/°F)	1.1916	1.1874	1.1701	1.1728		
Pattern Factor	.2622	.2572	.2367	.2410		
II. 75% Dilution Hole Area						
A. Emissions						
CO (ppm)			556.1	355.9	75.1	
C_3H_8 (ppm)			18.2	5.2	4.0	
NO_x (ppm NO_2)			31.8	50.6	87.7	
Smoke Number			44.9	44.9	37.7	
CO_2 (%)			3.47	3.84	4.44	
B. Gas Analysis						
Comb. Eff. (%)			99.21	99.54	99.88	
$F\text{-}A_{chem}/F\text{-}A_{mech}$			1.101	1.131	1.128	
C. System Performance						
Pressure Drop (%)			3.12	3.14	3.20	
T_{max}/T_{avg} (°F/°F)			1.1191	1.1692	1.2015	
Pattern Factor			.1668	.2376	.2817	
III. 50% Dilution Hole Area						
A. Emissions						
CO (ppm)			966.5	751.7	228.1	52.4
C_3H_8 (ppm)			44.4	15.1	4.6	3.9
NO_x (ppm NO_2)			32.4	38.2	66.7	100.7
Smoke Number			43.1	46.8	45.2	39.2
CO_2 (%)			3.13	3.55	4.08	4.55
B. Gas Analysis						
Comb. Eff. (%)			98.47	98.99	99.71	99.90
$F\text{-}A_{chem}/F\text{-}A_{mech}$			1.036	1.053	1.019	1.042
C. System Performance						
Pressure Drop (%)			3.58	3.42	3.43	3.54
T_{max}/T_{avg} (°F/°F)			1.0950	1.1360	1.1394	1.1589
Pattern Factor			.1343	.1931	.1962	.2248
IV. 25% Dilution Hole Area						
A. Emissions						
CO (ppm)						58.8
C_3H_8 (ppm)						4.1
NO_x (ppm NO_2)						96.4
Smoke Number						44.6
CO_2 (%)						4.33
B. Gas Analysis						
Comb. Eff. (%)						99.89
$F\text{-}A_{chem}/F\text{-}A_{mech}$						.952
C. System Performance						
Pressure Drop (%)						4.35
T_{max}/T_{avg} (°F/°F)						1.1208
Pattern Factor						.1710

TABLE 59. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR MODIFIED CONVENTIONAL LINER NO. 5

MODIFIED CONVENTIONAL NO. 5, EX-115257, NOZZLE EX-114779, 2-POSITION ACT 9-20-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1514.	0.15	72.25	21.513	62.434	3.583	87.530	17.63
1517.	0.00	106.72	4.262	41.546	4.027	49.835	36.20
1518.	0.15	138.89	1.513	28.059	4.626	34.198	41.63
1522.	0.45	163.52	0.469	12.614	5.949	19.032	41.10
1525.	0.20	207.18	0.372	11.774	5.655	17.801	45.18
1526.	0.05	251.34	0.290	2.499	7.891	10.680	39.20
CYCLE TOTALS		159.26	1.998	17.008	5.692	24.698	45.18
PERCENT OF BASELINE		99.50	87.36	71.00	105.47	78.06	

MODIFIED CONVENTIONAL NO. 5, EX-115257, NOZZLE EX-114779, 2-POSITION INT 9-20-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1514.	0.15	72.25	21.513	62.434	3.583	87.530	17.63
1517.	0.00	106.72	4.262	41.546	4.027	49.835	36.20
1518.	0.15	138.89	1.513	28.059	4.626	34.198	41.63
1522.	0.45	163.52	0.469	12.614	5.949	19.032	41.10
0.	0.20	207.00	2.140	30.000	4.640	36.780	0.00
1527.	0.05	260.41	0.293	2.693	7.257	10.243	44.58
CYCLE TOTALS		159.68	2.452	21.709	5.383	29.545	44.58
PERCENT OF BASELINE		99.76	107.21	90.62	99.75	93.38	

Figure 82. Modified Conventional Liner No. 6, EX-115860.

The conclusions from the combustor tests of liners No. 5 and 6 stress the point that overleaning the primary zone does not allow adequate consumption of CO to occur to achieve the 50% reduction in total emissions. Thus the primary zone must be richened for CO and CH_x reduction. The thick-walled primary air tubes may have adversely affected the primary zone recirculation by their excessive blockage. Thus, for the next modified conventional configuration, the plunged tubes were replaced with formed sheet metal, and the diameter of the primary holes was further reduced.

Modified Conventional Liner No. 7

The modified conventional liner No. 7 was changed from the previous design to have a new smaller-diameter set of sheet metal plunged primary holes to re-richen the primary zone for the reduction of CH_x and CO emissions. The primary holes were reduced in diameter from .652 inch to .500 inch.

TABLE 60. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 6 HAVING VARIABLE DILUTION GEOMETRY AND USING DDA AIRBLAST FUEL NOZZLE EX-114779 WITH SCHEDULED PILOT FLOWS AT MODEL 250-C20B ENGINE CONDITIONS

	Opr'l	Percent Power				
	Idle	25	40	55	75	100
Pilot Flow Rate (lb/hr)	70.	60.	40.	20.	20.	10.
I. 100% Dilution Hole Area						
A. Emissions						
CO (ppm)	435.9	318.4	211.8			
C_3H_8 (ppm)	14.4	10.3	4.6			
NO_x (ppm NO_2)	27.8	42.0	55.4			
Smoke Number	7.2	15.0	16.9			
CO_2 (%)	2.45	3.16	3.31			
B. Gas Analysis						
Comb. Eff. (%)	99.12	99.49	99.67			
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.015	1.104	1.054			
C. System Performance						
Pressure Drop (%)	3.55	3.43	3.49			
T_{max}/T_{avg} (°F/°F)	1.3800	1.2294	1.2091			
Pattern Factor	.5199	.3192	.2938			
II. 75% Dilution Hole Area						
A. Emissions						
CO (ppm)			214.1	146.8		
C_3H_8 (ppm)			4.6	2.1		
NO_x (ppm NO_2)			46.9	60.9		
Smoke Number			11.5	19.9		
CO_2 (%)			3.31	3.73		
B. Gas Analysis						
Comb. Eff. (%)			99.67	99.79		
$F\text{-}A_{chem}/F\text{-}A_{mech}$			1.067	1.082		
C. System Performance						
Pressure Drop (%)			3.75	3.78		
T_{max}/T_{avg} (°F/°F)			1.1745	1.1647		
Pattern Factor			.2473	.2335		
III. 50% Dilution Hole Area						
A. Emissions						
CO (ppm)	651.5		300.9	237.6	81.3	32.3
C_3H_8 (ppm)	30.8		6.0	4.4	3.0	2.1
NO_x (ppm NO_2)	20.6		39.6	64.6	84.8	120.5
Smoke Number	3.2		9.4	10.5	19.4	22.4
CO_2 (%)	2.500		3.26	3.79	4.33	4.98
B. Gas Analysis						
Comb. Eff. (%)	98.70		99.54	99.68	99.88	99.93
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.044		1.051	1.109	1.105	1.077
C. System Performance						
Pressure Drop (%)	3.97		4.31	4.57	4.17	4.04
T_{max}/T_{avg} (°F/°F)	1.2836		1.1950	1.2176	1.1892	1.1653
Pattern Factor	.3916		.2793	.3156	.2706	.2337
IV. 25% Dilution Hole Area						
A. Emissions						
CO (ppm)				349.4	177.1	51.3
C_3H_8 (ppm)				4.2	2.6	1.9
NO_x (ppm NO_2)				45.4	56.8	85.9
Smoke Number				10.3	13.9	13.5
CO_2 (%)				3.95	4.06	4.72
B. Gas Analysis						
Comb. Eff. (%)				99.57	99.77	99.92
$F\text{-}A_{chem}/F\text{-}A_{mech}$				1.157	1.031	1.017
C. System Performance						
Pressure Drop (%)				5.26	5.51	5.50
T_{max}/T_{avg} (°F/°F)				1.1793	1.1828	1.1954
Pattern Factor				.2639	.2694	.2841

TABLE 61. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR MODIFIED CONVENTIONAL LINER NO. 6

MODIFIED CONVENTIONAL NO. 6, EX-115860, NOZZLE EX-114779, 2-POSITION ACT 9-27-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1553.	0.15	72.98	4.022	54.105	2.817	60.944	3.17
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1557.	0.15	139.16	0.621	19.816	4.287	24.724	9.38
1558.	0.45	165.45	0.267	10.609	5.816	16.692	7.70
1564.	0.20	210.98	0.215	9.319	4.907	14.441	13.91
1565.	0.05	262.58	0.134	2.309	6.348	8.791	13.51
CYCLE TOTALS		161.60	0.543	13.734	5.221	19.498	13.91
PERCENT OF BASELINE		100.96	23.73	57.33	96.75	61.62	

MODIFIED CONVENTIONAL NO. 6, EX-115860, NOZZLE EX-114779, 2-POSITION INT 9-27-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.15	72.98	4.022	54.105	2.817	60.944	0.00
0.	0.00	108.00	1.530	33.700	3.500	38.730	0.00
0.	0.15	139.16	0.621	19.816	4.287	24.724	0.00
0.	0.45	165.45	0.267	10.609	5.816	16.692	0.00
0.	0.20	210.98	0.260	9.319	5.300	14.879	0.00
0.	0.05	262.58	0.150	2.309	6.348	8.807	0.00
CYCLE TOTALS		161.60	0.556	13.734	5.324	19.613	0.00
PERCENT OF BASELINE		100.96	24.30	57.33	98.65	61.99	

A summary of the test data recorded for this combustor is presented in Table 62. Four different dilution hole areas were used during the rig testing, accounting for 100%, 75%, 50%, and 25% open dilution holes. Using the 100% open dilution setting for low powers up through 40% power and the 50% open setting for all higher power settings resulted in 21% more NO_x than from the baseline liner, as shown in Table 63. Holding NO_x to base-line levels and using the expanded emissions data set derived from the plots of the actual data showed that, for a two-dilution setting, combinations of 60% open for 40% power and below and 25% open for operation above 40% power, the reduction in total emissions was only 47%.

Because this and the previous two combustor designs were unable to make any progress toward meeting the emissions goals by simple changes in primary hole sizing, which was the temperature controlling mechanism, a method for adjusting volume or residence time was incorporated into the next configuration. The two-position dilution-geometry system lended itself to the sizing and placement of two separate and independently operating dilution hole systems. For low power, a set of large area holes set well downstream permitted a richened primary zone (higher flame temperature) with a large volume (long residence time) to consume carbon, carbon monoxide, and unburned hydrocarbons. A second set of dilution holes controlled by the same geometry band was designed for high power, and they were designed to be well upstream (2.00 inches) of the other set of holes and were of small area to lean the primary zone (lower flame temperature) with a small volume (short residence time) to suppress the formation of nitrogen oxide. All of the subsequent modified conventional liner designs used this two-row configuration. This technique also allowed the circumferential hole locations to be independently designed so as to give better exhaust temperature profiles at high and low power operating conditions.

Modified Conventional Liner No. 8

This modified conventional liner, shown in Figures 83 and 84, was changed from the previous design to have (1) a new airblast nozzle, EX-115870A (refer to earlier discussion of differences in airblast nozzles presented under the heading, Prechamber Liner No. 11), in which the main fuel is sprayed normally into the swirler air through a row of twenty .020-inch diameter holes (Figure 85), and (2) an additional set of four .625-inch diameter, variable-area dilution holes located 2.00 inches up-

TABLE 62. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 7 (EX-115887) HAVING VARIABLE DILUTION GEOMETRY AND USING DDA AIRBLAST FUEL NOZZLE (EX-114779) WITH SCHEDULED FLOWS AT MODEL 250-C20B ENGINE CONDITIONS

	Opr'l Idle	Percent Power 25	40	55	75	100
Pilot Flow Rate (lb/hr)	70.	60.	40.	20.	10.	10.
I. 100% Dilution Hole Area						
A. Emissions						
CO (ppm)	386.4	175.0	99.1			
C_3H_8 (ppm)	12.3	2.6	.4			
NO_x (ppm NO_2)	28.7	41.6	53.7			
Smoke Number	7.1	6.1	5.8			
CO_2 (%)	2.50	3.11	3.31			
B. Gas Analysis						
Comb. Eff. (%)	99.23	99.72	99.84			
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.041	1.092	1.054			
C. System Performance						
Pressure Drop (%)	3.63	4.16	4.17			
T_{max}/T_{avg} (°F/°F)	1.369	1.237	1.237			
Pattern Factor	.5046	.3273	.3343			
II. 75% Dilution Hole Area						
A. Emissions						
CO (ppm)	404.2	192.0	116.2	76.7	53.4	
C_3H_8 (ppm)	9.4	1.6	.8	.3	.4	
NO_x (ppm NO_2)	26.7	36.7	51.0	68.2	97.1	
Smoke Number	3.6	5.5	5.7	5.8	8.8	
CO_2 (%)	2.60	3.16	3.36	3.68	4.06	
B. Gas Analysis						
Comb. Eff. (%)	99.24	99.70	99.82	99.88	99.90	
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.073	1.105	1.066	1.070	1.034	
C. System Performance						
Pressure Drop (%)	3.82	4.17	3.98	4.28	4.15	
T_{max}/T_{avg} (°F/°F)	1.271	1.205	1.132	1.157	1.169	
Pattern Factor	.3717	.2854	.1872	.2229	.2405	
III. 50% Dilution Hole Area						
A. Emissions						
CO (ppm)	587.4	284.1	162.8	93.5	53.4	26.1
C_3H_8 (ppm)	16.8	2.9	.5	2.1	.4	.3
NO_x (ppm NO_2)	22.6	34.7	46.5	60.2	84.5	144.2
Smoke Number	2.2	5.0	4.4	--	5.6	5.1
CO_2 (%)	2.55	3.06	3.31	3.63	4.22	4.95
B. Gas Analysis						
Comb. Eff. (%)	98.89	99.55	99.76	99.85	99.91	99.93
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.091	1.088	1.050	1.070	1.058	1.046
C. System Performance						
Pressure Drop (%)	4.68	4.56	4.48	4.55	4.83	4.62
T_{max}/T_{avg} (°F/°F)	1.318	1.179	1.169	1.146	1.142	1.161
Pattern Factor	.4374	.2518	.2411	.2104	.2026	.2286
IV. 25% Dilution Hole Area						
A. Emissions						
CO (ppm)			397.0	218.7	80.8	
C_3H_8 (ppm)			3.3	1.0	.3	
NO_x (ppm NO_2)			38.2	43.8	67.8	
Smoke Number			2.9	3.0	5.3	
CO_2 (%)			3.18	3.44	4.06	
B. Gas Analysis						
Comb. Eff. (%)			99.41	99.69	99.88	
$F\text{-}A_{chem}/F\text{-}A_{mech}$			1.028	1.014	1.019	
C. System Performance						
Pressure Drop (%)			5.51	5.56	5.66	
T_{max}/T_{avg} (°F/°F)			1.292	1.242	1.212	
Pattern Factor			.4214	.3576	.3073	

TABLE 63. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR MODIFIED CONVENTIONAL LINER NO. 7

MODIFIED CONVENTIONAL NO. 7, EX-115887, NOZZLE EX-114779, 2-POSITION ACT 11-4-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1641.	0.15	70.55	1.624	32.409	3.955	37.988	7.11
1645.	0.00	107.11	0.292	12.596	4.921	17.809	6.09
1649.	0.15	135.81	0.043	6.482	5.773	12.298	5.76
1653.	0.45	163.18	0.198	5.688	6.012	11.898	0.00
1656.	0.20	217.63	0.034	2.785	7.233	10.052	5.60
1658.	0.05	267.54	0.023	1.156	10.481	11.660	5.14
CYCLE TOTALS		161.29	0.213	6.382	6.547	13.142	7.11
PERCENT OF BASELINE		100.77	9.32	26.64	121.31	41.54	

MODIFIED CONVENTIONAL NO. 7, EX-115887, NOZZLE EX-114779, 2-POSITION INT 11-4-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.15	71.00	1.580	43.700	3.380	48.660	0.00
0.	0.00	107.30	0.240	16.600	4.270	21.110	0.00
0.	0.15	135.00	0.100	9.000	5.200	14.300	0.00
1654.	0.45	163.53	0.099	13.233	4.950	18.282	2.99
1657.	0.20	214.20	0.060	4.207	5.802	10.069	5.32
0.	0.05	265.30	0.060	0.200	8.220	8.480	0.00
CYCLE TOTALS		160.59	0.184	11.235	5.375	16.794	5.32
PERCENT OF BASELINE		100.34	8.03	46.90	99.59	53.08	

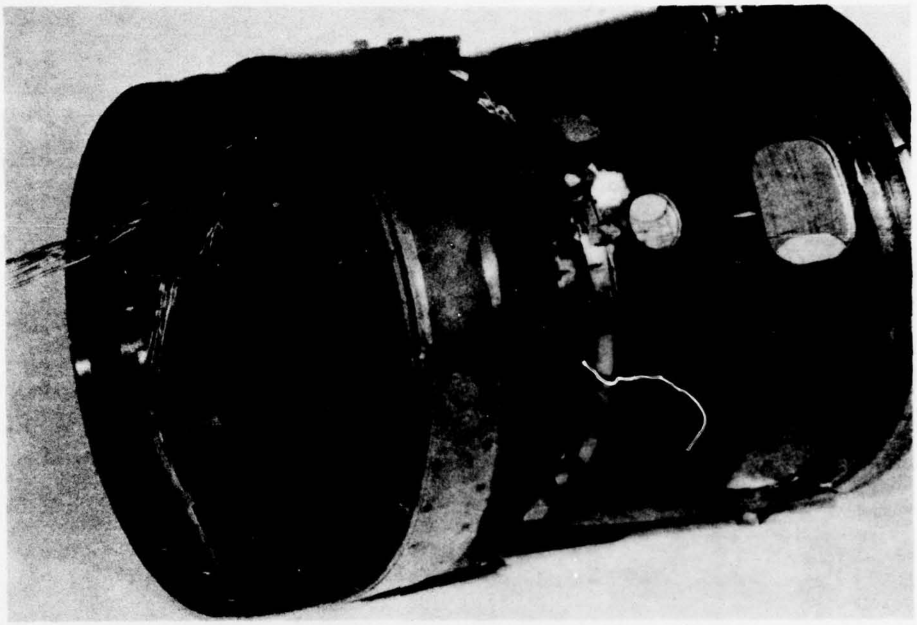

Figure 83. Modified Conventional Liner No. 8, EX-115895, External View.

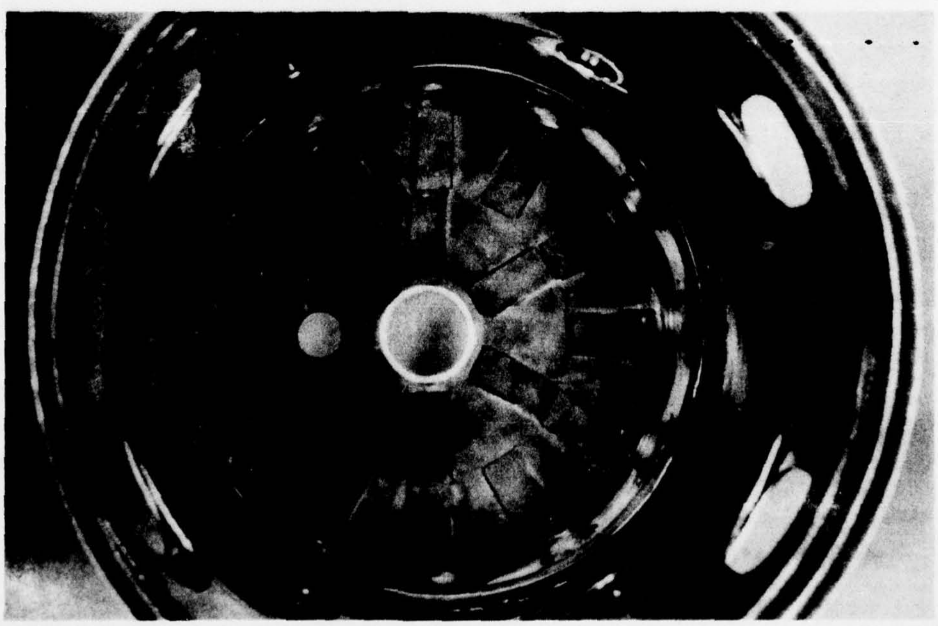

Figure 84. Modified Conventional Liner No. 8, EX-115895, Internal View.

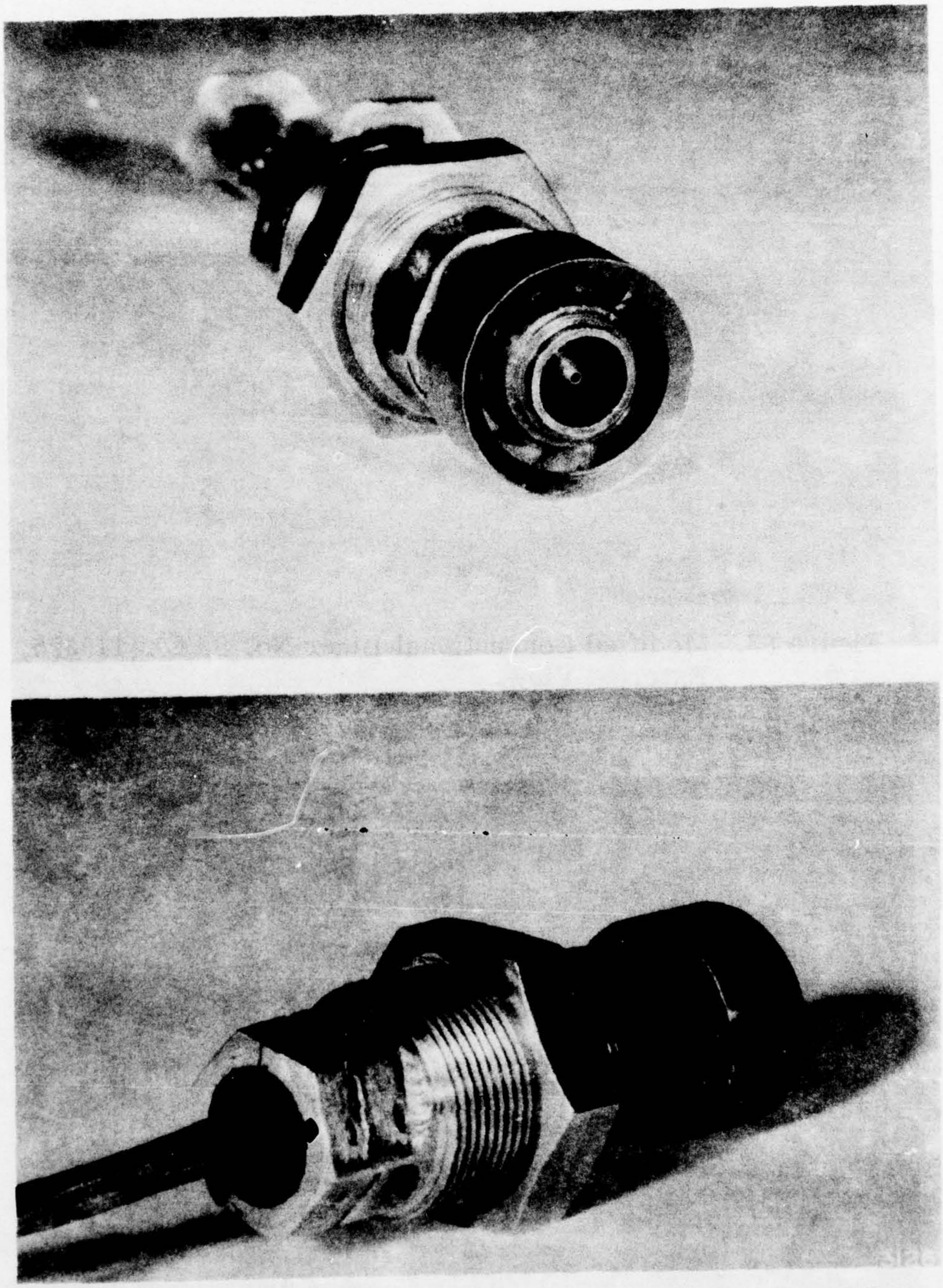

Figure 85. Airblast Fuel Nozzle EX-115870 with Simplex Pilot.

stream of the existing dilution holes and 60° on either side of the horizontal plane. These four holes were located radially beneath four existing holes in the air distribution basket in the outer case and became fully open when the downstream dilution holes were fully closed. The purpose of these holes was to reduce the intermediate zone residence time, in addition to leaning the primary zone, thus suppressing NO_x generation at high power.

A summary of the test data recorded for this combustor is presented in Table 64. Five different dilution hole area settings were used during the rig testing, accounting for 100%, 75%, 50%, 25%, and 0% open dilution holes. The only combination of two-position dilution hole settings that is possible from the actual data was a 50%-open dilution setting from idle through 55% power and a 0%-open setting above 55% power. From the top half of Table 65, where these results are shown, both NO_x and total emissions were high. Using the expanded interpolated data set in the bottom half of Table 65, the NO_x could be maintained below baseline, but the total emissions rose to 61% of baseline.

Modified Conventional Liner No. 9

Compared with the previous modified conventional liner configuration, this liner No. 9 received the following modifications:

1. The primary holes were returned to .562-inch diameter to retain the NO_x margin and to reduce the pressure drop slightly.
2. One of every three .172-inch diameter dilution zone film-cooling holes were closed, reducing their number from 48 to 32, to improve radial temperature distribution in the exhaust annulus and to lean out the primary zone by a small amount.
3. The four .625-inch diameter dilution holes, 60° on either side of the horizontal axis, were replaced with two .875 inch diameter holes located on the horizontal axis. This change was to reduce the hot sector in the exhaust annulus adjacent to the inlet air tubes, thus improving the exhaust radial temperature pattern.

An external photograph of this liner is shown in Figure 86. A summary of the test data recorded for this combustor is presented in Table 66. During the test, five different dilution geometry settings were used: 100%, 75%, 50%, 25%, and 0% open. From the actual test data, the best two-position emissions performance was 100% open geometry setting for low power through 40% power and 50% open setting at the higher power levels. Using the expanded data set, the lowest two-position NO_x level over the LOH duty cycle conditions was just under 105% of baseline, as shown in Table 67, resulting in the total emissions being 62% of the total baseline level.

AD-A038 550 GENERAL MOTORS CORP INDIANAPOLIS IND DETROIT DIESEL --ETC F/G 21/5
LOW-EMISSIONS COMBUSTOR DEMONSTRATION.(U)
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3 OF 5
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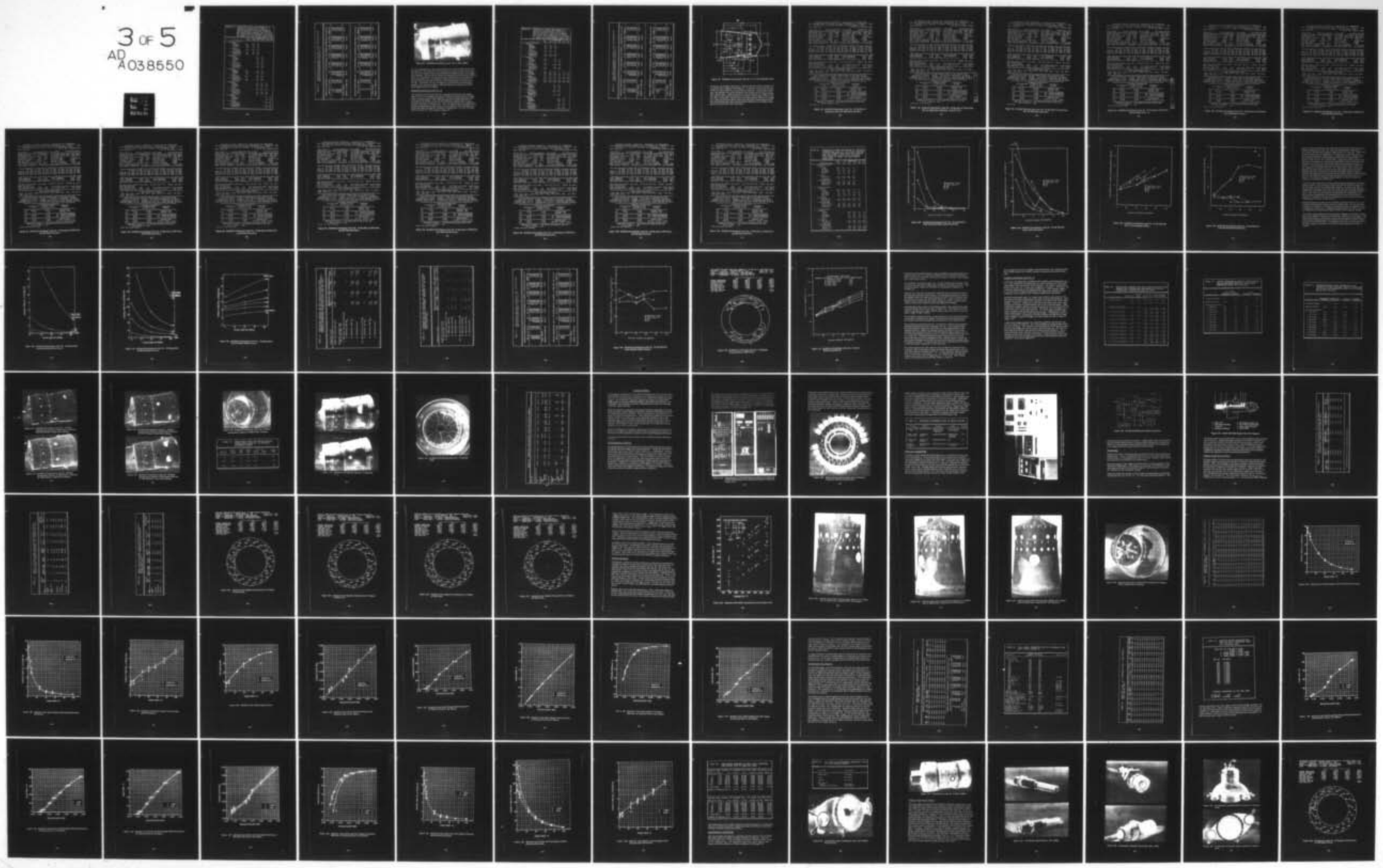

TABLE 64. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 8 HAVING VARIABLE DILUTION GEOMETRY AND USING DDA AIRBLAST FUEL NOZZLE (EX-115870A) WITH SCHEDULED AIR FLOWS AT MODEL 250-C20B ENGINE CONDITIONS

	Opr'l	Percent Power				
	Idle	25	40	55	75	100
Pilot Flow Rate (lb/hr)	37.	35.	35.	20.	20.	10.
I. 100% Dilution Hole Area						
A. Emissions						
CO (ppm)	587.4	245.0	142.9			
C_3H_8 (ppm)	54.4	6.4	1.4			
NO_x (ppm NO_2)	30.8	47.4	63.6			
Smoke Number	13.6	12.2	13.2			
CO_2 (%)	2.60	3.06	3.36			
B. Gas Analysis						
Comb. Eff. (%)	98.76	99.59	99.78			
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.105	1.053	1.071			
C. System Performance						
Pressure Drop (%)	3.75	3.66	3.69			
T_{max}/T_{avg} (°F/°F)	1.167	1.165	1.160			
Pattern Factor	.2260	.2274	.2242			
II. 75% Dilution Hole Area						
A. Emissions						
CO (ppm)			154.7	88.7		
C_3H_8 (ppm)			1.6	.5		
NO_x (ppm NO_2)			57.8	70.4		
Smoke Number			9.2	8.1		
CO_2 (%)			3.31	3.63		
B. Gas Analysis						
Comb. Eff. (%)			99.76	99.86		
$F\text{-}A_{chem}/F\text{-}A_{mech}$			1.055	1.066		
C. System Performance						
Pressure Drop (%)			4.24	4.23		
T_{max}/T_{avg} (°F/°F)			1.146	1.123		
Pattern Factor			.2046	.1739		
III. 50% Dilution Hole Area						
A. Emissions						
CO (ppm)	751.7		205.1	112.4		
C_3H_8 (ppm)	49.2		1.9	.6		
NO_x (ppm NO_2)	24.4		49.6	62.2		
Smoke Number	6.7		5.9	4.8		
CO_2 (%)	2.50		3.31	3.68		
B. Gas Analysis						
Comb. Eff. (%)	98.46		99.69	99.83		
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.054		1.059	1.094		
C. System Performance						
Pressure Drop (%)	4.26		4.70	4.50		
T_{max}/T_{avg} (°F/°F)	1.293		1.227	1.156		
Pattern Factor	.4021		.3234	.2226		
IV. 25% Dilution Hole Area						
A. Emissions						
CO (ppm)			318.4	192.0	73.6	
C_3H_8 (ppm)			3.7	1.0	.2	
NO_x (ppm NO_2)			41.2	50.2	73.8	
Smoke Number			5.7	6.8	8.6	
CO_2 (%)			3.11	3.42	4.00	
B. Gas Analysis						
Comb. Eff. (%)			99.50	99.72	99.89	
$F\text{-}A_{chem}/F\text{-}A_{mech}$			.991	1.012	1.014	
C. System Performance						
Pressure Drop (%)			5.10	4.96	5.50	
T_{max}/T_{avg} (°F/°F)			1.204	1.122	1.130	
Pattern Factor			.2965	.1786	.1896	
V. 0% Dilution Hole Area						
A. Emissions						
CO (ppm)					80.8	28.2
C_3H_8 (ppm)					.2	.2
NO_x (ppm NO_2)					76.1	114.2
Smoke Number					8.3	5.1
CO_2 (%)					4.33	5.00
B. Gas Analysis						
Comb. Eff. (%)					99.89	99.94
$F\text{-}A_{chem}/F\text{-}A_{mech}$					1.101	1.080
C. System Performance						
Pressure Drop (%)					5.50	5.39
T_{max}/T_{avg} (°F/°F)					1.179	1.184
Pattern Factor					.2605	.2657

TABLE 65. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR MODIFIED CONVENTIONAL LINER NO. 8

MODIFIED CONVENTIONAL NO. 8, EX-115895,NOZZLE EX-115870A,2-POSITION ACT 12-12-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1739.	0.15	68.90	6.463	62.693	3.337	72.493	6.70
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1745.	0.15	134.82	0.198	13.449	5.340	18.987	5.91
1749.	0.45	161.99	0.060	6.889	6.261	13.210	4.76
1752.	0.20	215.25	0.019	4.266	6.606	10.891	8.32
1753.	0.05	264.26	0.016	1.271	8.465	9.752	5.06
CYCLE TOTALS		159.72	0.477	10.159	6.231	16.866	8.32
PERCENT OF BASELINE		99.79	20.86	42.41	115.45	53.31	

MODIFIED CONVENTIONAL NO. 8, EX-115895,NOZZLE EX-115870A,2-POSITION INT 12-12-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	I TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
0.	0.15	69.00	6.460	54.400	3.900	64.760	0.00
0.	0.00	107.30	0.820	19.500	4.960	25.280	0.00
0.	0.15	135.00	0.500	23.000	4.300	27.800	0.00
0.	0.45	164.30	0.120	12.900	4.950	17.970	0.00
0.	0.20	211.20	0.030	3.900	6.300	10.230	0.00
0.	0.05	265.30	0.020	1.000	7.770	8.790	0.00
CYCLE TOTALS		160.04	0.546	13.500	5.390	19.436	0.00
PERCENT OF BASELINE		99.99	23.87	56.36	99.87	61.43	

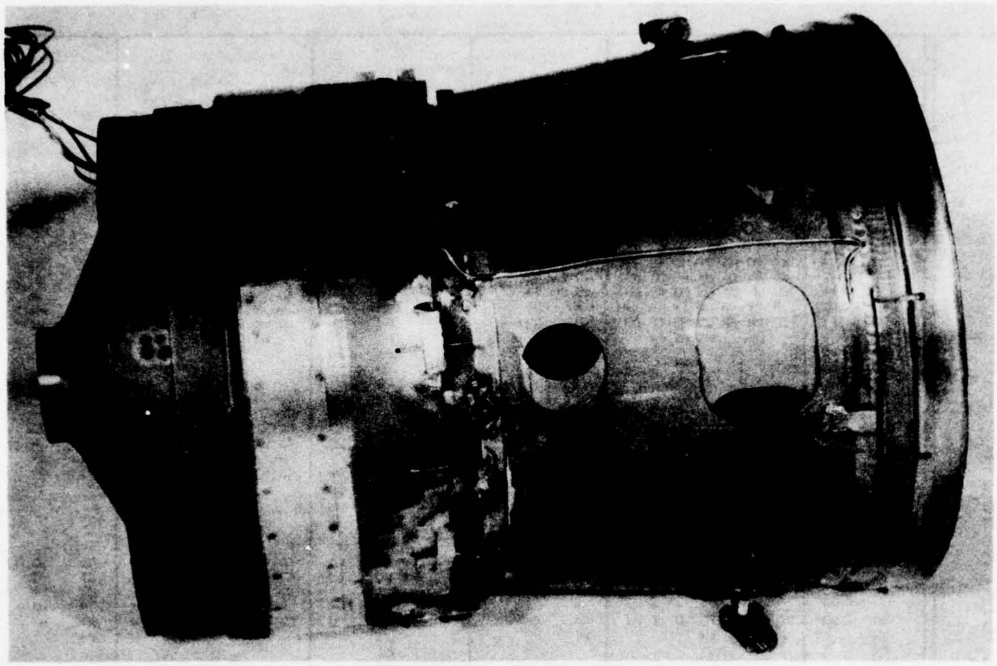

Figure 86. Modified Conventional Liner No. 9, EX-116289.

For this configuration, NO_x concentrations less than baseline levels were not obtained. Even where CO concentrations equaled baseline CO levels, the NO_x concentrations from this modified conventional liner were higher than baseline. Also at the 0% dilution setting, where the low power dilution holes were completely closed and the pair of high power holes upstream were completely open, the exhaust temperature pattern was quite poor, having a hot section near the bottom of the annulus and a cold section at the top. Therefore, the next configuration concentrated on leaning the primary zone and improving the exhaust temperature pattern at the 0%-open dilution geometry setting.

Modified Conventional Liner No. 10

The modified conventional liner was changed from the previous design, liner No. 9, by returning to two pairs of upstream dilution holes for high power running instead of the single pair of holes having equal area used on the previous design. The four new holes were again 0.625 inch in diameter but were located 30° above and below horizontal axis, adjacent to each of the inlet-air feed arms. Also, to enhance the air supplied to the 0.562-inch diameter primary holes, a set of twelve 0.250-inch diameter holes was added through the convection cooling shell. A cross-sectional sketch of Liner No. 10 is shown in Figure 87.

TABLE 66. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 9 HAVING VARIABLE DILUTION GEOMETRY AND USING DDA AIRBLAST FUEL NOZZLE EX-115870C WITH SCHEDULED PILOT FLOWS AT MODEL 250-C20B ENGINE CONDITIONS

	Opr'l Idle	Percent Power 25	40	55	75	100
Pilot Flow Rate (lb/hr)	72	60	40	30	20	20
I. 100% Dilution Hole Area						
A. Emissions						
CO (ppm)	465.2	196.3	116.2			
C_3H_8 (ppm)	28.7	3.7	1.4			
NO_x (ppm NO_2)	26.2	41.4	55.6			
Smoke Number	4.5	2.9	5.8			
CO_2 (%)	2.50	3.00	3.31			
B. Gas Analysis						
Comb. Eff. (%)	99.03	99.67	99.81			
F-Achem/F-Amech	1.042	1.040	1.071			
C. System Performance						
Pressure Drop (%)	3.77	4.01	3.82			
T_{max}/T_{avg} (°F/°F)	1.1401	1.1404	1.1504			
Pattern Factor	.1892	.1923	.2089			
II. 75% Dilution Hole Area						
A. Emissions						
CO (ppm)	651.5		146.8	77.7		
C_3H_8 (ppm)	32.8		1.4	.2		
NO_x (ppm NO_2)	24.5		51.6	66.0		
Smoke Number	4.0		5.0	5.6		
CO_2 (%)	2.50		3.31	3.57		
B. Gas Analysis						
Comb. Eff. (%)	98.69		99.77	99.87		
F-Achem/F-Amech	1.048		1.060	1.056		
C. System Performance						
Pressure Drop (%)	4.22		4.28	4.32		
T_{max}/T_{avg} (°F/°F)	1.2095		1.2406	1.2221		
Pattern Factor	.2852		.3347	.3122		
III. 50% Dilution Hole Area						
A. Emissions						
CO (ppm)	1004.2	349.4	183.4	90.7	44.9	23.1
C_3H_8 (ppm)	49.3	6.8	1.4	.1	.2	.1
NO_x (ppm NO_2)	24.2	38.4	49.6	60.9	92.7	125.4
Smoke Number	5.9	3.2	4.5	4.5	1.9	1.7
CO_2 (%)	2.55	3.16	3.36	3.68	4.27	4.66
B. Gas Analysis						
Comb. Eff. (%)	98.06	99.46	99.72	99.86	99.92	99.94
F-Achem/F-Amech	1.079	1.101	1.067	1.072	1.076	1.068
C. System Performance						
Pressure Drop (%)	4.41	4.31	4.42	4.55	4.51	4.82
T_{max}/T_{avg} (°F/°F)	1.1632	1.1272	1.1281	1.1421	1.1467	1.1255
Pattern Factor	.2182	.1736	.1768	.1962	.2020	.1747
IV. 25% Dilution Hole Area						
A. Emissions						
CO (ppm)			382.9	187.6		
C_3H_8 (ppm)			3.7	.7		
NO_x (ppm NO_2)			42.5	55.8		
Smoke Number			4.5	5.7		
CO_2 (%)			3.26	3.63		
B. Gas Analysis						
Comb. Eff. (%)			99.44	99.74		
F-Achem/F-Amech			1.055	1.050		
C. System Performance						
Pressure Drop (%)			5.24	5.35		
T_{max}/T_{avg} (°F/°F)			1.2081	1.2269		
Pattern Factor			.2899	.3162		
V. 0% Dilution Hole Area						
A. Emissions						
CO (ppm)				289.6	135.2	
C_3H_8 (ppm)				.9	.3	
NO_x (ppm NO_2)				55.9	71.5	
Smoke Number				4.6	4.5	
CO_2 (%)				3.84	4.11	
B. Gas Analysis						
Comb. Eff. (%)				99.63	99.82	
F-Achem/F-Amech				1.122	1.047	
C. System Performance						
Pressure Drop (%)				5.74	5.87	
T_{max}/T_{avg} (°F/°F)				1.1971	1.2131	
Pattern Factor				.2779	.3004	

TABLE 67. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR MODIFIED CONVENTIONAL LINER NO. 9

MODIFIED CONVENTIONAL NO. 9, EX-116289,NOZZLE EX-115870C, 2-POSITION ACT 1-31-75

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1771.	0.15	71.75	3.775	38.860	3.595	46.230	4.49
1775.	0.00	206.92	0.413	13.884	4.807	19.104	2.92
1776.	0.15	130.27	0.149	7.718	6.071	13.938	5.80
1781.	0.45	165.25	0.012	5.451	6.016	11.479	4.51
1785.	0.20	211.24	0.017	2.351	7.973	10.341	1.93
1787.	0.05	243.02	0.009	1.103	9.845	10.957	1.66
CYCLE TOTALS		159.06	0.285	6.834	6.671	13.790	5.80
PERCENT OF BASELINE		99.38	12.44	28.53	123.62	43.59	

MODIFIED CONVENTIONAL NO. 9, EX-116289,NOZZLE EX-115870C, 2-POSITION INT 1-31-75

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1771.	0.15	71.75	3.775	38.860	3.595	46.230	4.49
1775.	0.00	206.92	0.413	13.884	4.807	19.104	2.92
0.	0.15	131.30	0.460	29.800	4.510	34.770	0.00
0.	0.45	165.00	0.090	13.000	5.400	18.490	0.00
0.	0.20	211.20	0.050	4.300	6.500	10.850	0.00
0.	0.05	245.00	0.030	2.000	7.830	9.860	0.00
CYCLE TOTALS		159.20	0.370	13.672	5.647	19.688	4.49
PERCENT OF BASELINE		99.46	16.16	57.07	104.63	62.23	

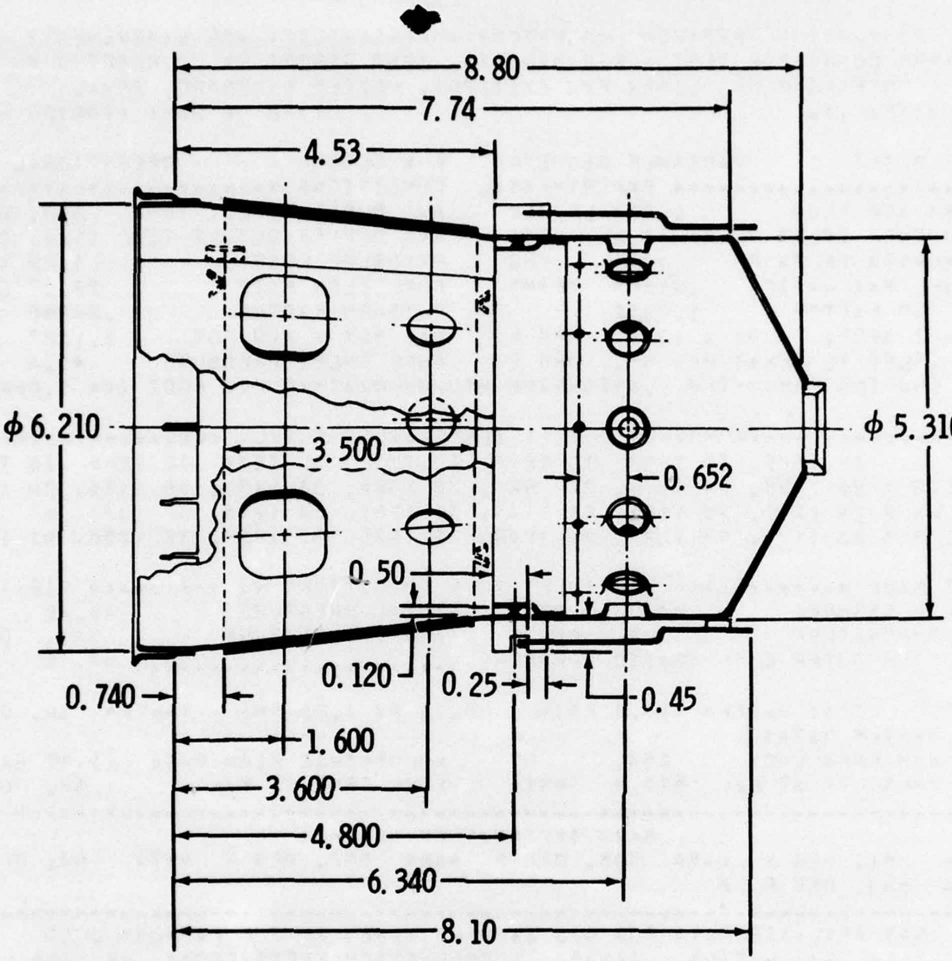

Figure 87. Modified Conventional Liner No. 10—Cross-Sectional View.

During the rig testing of this liner, fourteen data sets were recorded and are presented in Figures 88 through 101. A summary of the test data recorded for this combustor is presented in Table 68. Three different dilution area settings were used during the rig testing, accounting for 100%, 50%, and 0% open. Exhaust emissions from this liner are compared with the baseline liner exhaust emissions in Figures 102 through 105 for CH_x, CO, NO_x, and smoke. Data points at the same dilution hole area settings are connected by dashed lines, while the solid lines connecting the modified conventional liner data represent those dilution area settings producing the best LOH duty cycle emissions.

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        COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A  , READING #  1800
      MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C. JP-4.
TEST DATE: 174                                  TIME OF DAY: 1700:29 HOURS

CYCLE POINT  2    VARIABLE GEOMETRY   0 % CLOSED         OPERATIONAL IDLE
*********************** EXPERIMENTAL  CONDITIONS ***********************
BURNER AIR FLOW          1.874 LB/SEC   AVG BURNER INLET TEMP    303. DEG F
AVG BURNER INLET PRES  44.2    PSIA    AVG BURNER OUTLET TEMP 1178. DEG F
AVG BURNER DELTA P      3.35    "HG    PRESSURE LOSS              3.39 %
OVERALL F/A RATIO      .01165  (F/M)   FUEL FLOW RATE            70.17 LB/HR
AIR LOAD FACTOR        1.0452          PATTERN FACTOR           .20556
BOT HOT SPOT:  # 21 = 1358.  DEG F     MAX BOT / AVG BOT        1.1527
FUEL INLET TEMPERATURE  65.  DEG F     FUEL INLET PRESSURE        41.4  PSIA
HEAT LOADING PARAMETER  .43798E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
          ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1358. 24 1138. 27  944. 30 1308. 33 1250. 36 1126. 39 1144.
ANNULUS 2 22 1261. 25 1191. 28 1148. 31 1261. 34 1295. 37 1071. 40 1343.
ANNULUS 3 23 1109. 26 1023. 29 1049. 32 1225. 35 1058. 38 1256. 41 1179.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE            44.23   PSIA   TOTAL PRESSURE            44.20   PSIA
AIR TEMPERATURE           303.   DEG F   AIR TEMPERATURE           303.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................  44.16    PSIA

AIR FLOW DATA: P-REF= 116.3 PSIA   DELTA P= 1.05 "HG    T-REF=  39. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY        254.      HZ    VOLUMETRIC FLOW RATE  11.06 GAL/HR
FUEL PRESSURE AT F/M   529.0   PSIA    FUEL TEMP AT F/M             60.  DEG F
--------------------------------------------------------------------------
                        SKIN TEMPERATURE SURVEY:
 #44=  581. DEG F  #45=  596. DEG F  #46=  597. DEG F  #47=   64. DEG F
 #48=  553. DEG F  #
--------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .012559    COMBUSTION EFFICIENCY:  98.6096 %
 MEASURED CO2: 2.550 %   MEASURED O2:    .17 %   CALCULATED O2: 17.39 %
ANALYSIS CHECK: F/A IS  .012978 WHEN CALCULATED USING MEASURED O2 VALUE
      ------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
         CONCENTRATION  EMISSIONS INDEX          INSTRUMENT
              PPM        LB/1000 LB FUEL           SOURCE
      ------------------------------------------------------------
      CO      634.95          53.334            BECKMAN NDIR
      CHX      30.75           4.070            BECKMAN  FID
      ------------------------------------------------------------
      NO       14.42           1.989       AMI  CHEMILUMINESCENCE
      NOX      26.22           3.618       AMI  CHEMILUMINESCENCE
      ------------------------------------------------------------
      NO       14.45           1.994            BECKMAN NDIR
      NOX      28.10           3.888       BECKMAN  (NDIR + NDUV)
      ------------------------------------------------------------
        ABSOLUTE HUMIDITY =    .00 GRAINS PER POUND OF DRY AIR
             SMOKE NUMBER =   8.61
 ALL PILOT.
```

Figure 88. Modified Conventional Liner No. 10 Rig Data at Operational Idle and 100% Open Geometry.

```
        COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A  , READING #  1801
      MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C. JP-4.
TEST DATE: 174                                      TIME OF DAY: 1722: 8 HOURS

CYCLE POINT  2    VARIABLE GEOMETRY    0 % CLOSED           OPERATIONAL IDLE
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          1.668 LB/SEC    AVG BURNER INLET TEMP     306. DEG F
AVG BURNER INLET PRES   44.5    PSIA     AVG BURNER OUTLET TEMP 1160. DEG F
AVG BURNER DELTA P       3.30    "HG     PRESSURE LOSS             3.64 %
OVERALL F/A RATIO       .01178  (F/M)    FUEL FLOW RATE           70.76 LB/HR
AIR LOAD FACTOR         1.0359           PATTERN FACTOR          .18479
BOT HOT SPOT:  # 21 = 1318.  DEG F       MAX BOT / AVG BOT       1.1361
FUEL INLET TEMPERATURE  65.  DEG F       FUEL INLET PRESSURE       43.1   PSIA
HEAT LOADING PARAMETER  .43861E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************* BURNER OUTLET TEMPERATURE SURVEY *******************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1318. 24 1092. 27  929. 30 1298. 33 1223. 36 1153. 39 1143.
ANNULUS 2 22 1188. 25 1126. 28 1162. 31 1249. 34 1302. 37 1065. 40 1297.
ANNULUS 3 23 1057. 26 1032. 29 1093. 32 1226. 35 1002. 38 1226. 41 1167.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE           44.55   PSIA    TOTAL PRESSURE           44.50   PSIA
AIR TEMPERATURE           306.   DEG F   AIR TEMPERATURE           306.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE......................  44.29   PSIA

AIR FLOW DATA: P-REF= 116.4 PSIA   DELTA P= 1.04 "HG    T-REF=  39. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY        256.     HZ    VOLUMETRIC FLOW RATE  11.15 GAL/HR
FUEL PRESSURE AT F/M  296.8    PSIA      FUEL TEMP AT F/M          59.  DEG F
-------------------------------------------------------------------------
                      SKIN TEMPERATURE SURVEY:
 #44=  585. DEG F  #45=  585. DEG F  #46=  583. DEG F  #47=   61. DEG F
 #48=  562. DEG F  #
-------------------------------------------------------------------------
       GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .012820   COMBUSTION EFFICIENCY:  97.7415 %
 MEASURED CO2: 2.550 %   MEASURED O2: 16.80 %   CALCULATED O2: 17.35 %
ANALYSIS CHECK: F/A IS  .013157 WHEN CALCULATED USING MEASURED O2 VALUE
       -----------------------------------------------------------
                      EMISSIONS MEASUREMENTS
         CONCENTRATION  EMISSIONS INDEX        INSTRUMENT
              PPM       LB/1000 LB FUEL          SOURCE

       -----------------------------------------------------------
        CO     916.41          76.103             BECKMAN NDIR
       CHX      86.72           8.722             BECKMAN  FID
       -----------------------------------------------------------
        NO      11.33           1.545        AMI  CHEMILUMINESCENCE
       NOX      24.22           3.304        AMI  CHEMILUMINESCENCE
       -----------------------------------------------------------
        NO      13.01           1.775             BECKMAN NDIR
       NOX      28.65           3.008        BECKMAN  [NDIR + NDUV]
       -----------------------------------------------------------
          ABSOLUTE HUMIDITY =   .00 GRAINS PER POUND OF DRY AIR
                SMOKE NUMBER =  0.87
  PILOT WF= 40.0 LB/HOUR.
```


Figure 89. Modified Conventional Liner No. 10 Rig Data at Operational Idle and 100% Open Geometry, 40 lb/hr Pilot.

```
        COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T53 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A  , READING #  1802
     MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C. JP-4.
TEST DATE: 174                                  TIME OF DAY: 1746:38 HOURS

CYCLE POINT  2     VARIABLE GEOMETRY  50 % CLOSED         OPERATIONAL IDLE
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW         1.571 LB/SEC     AVG BURNER INLET TEMP   305. DEG F
AVG BURNER INLET PRES  45.0    PSIA     AVG BURNER OUTLET TEMP 1149. DEG F
AVG BURNER DELTA P      3.80    "HG     PRESSURE LOSS             4.16 %
OVERALL F/A RATIO      .01156  (F/M)    FUEL FLOW RATE           70.17 LB/HR
AIR LOAD FACTOR        1.0274           PATTERN FACTOR          .25972
BOT HOT SPOT: # 22 = 1368.  DEG F       MAX BOT / AVG BOT       1.1909
FUEL INLET TEMPERATURE  63.  DEG F      FUEL INLET PRESSURE       42.0  PSIA
HEAT LOADING PARAMETER  .43067E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1350. 24 1234. 27  986. 30 1183. 33 1259. 36 1177. 39 1132.
ANNULUS 2 22 1368. 25 1245. 28 1074. 31 1181. 34 1229. 37  998. 40 1269.
ANNULUS 3 23 1038. 26  939. 29  995. 32 1133. 35 1105. 38 1073. 41 1142.

 LEFT SIDE ************* AIR INLET TUBE CONDITIONS ************* RIGHT SIDE
TOTAL PRESSURE            44.96   PSIA    TOTAL PRESSURE            44.97  PSIA
AIR TEMPERATURE           305.  DEG F    AIR TEMPERATURE           305.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................  44.61  PSIA

AIR FLOW DATA: P-REF= 116.4 PSIA   DELTA P= 1.05 "HG   T-REF=  38. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       254.      HZ    VOLUMETRIC FLOW RATE  11.06 GAL/HR
FUEL PRESSURE AT F/M  543.6   PSIA     FUEL TEMP AT F/M          60.  DEG F
--------------------------------------------------------------------------
                        SKIN TEMPERATURE SURVEY:
 #44=  694. DEG F  #45=  579. DEG F  #46=  592. DEG F  #47=   61. DEG F
 #48=  611. DEG F  #
--------------------------------------------------------------------------
     GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .014076    COMBUSTION EFFICIENCY:  97.6094 %
 MEASURED CO2: 2.901 %   MEASURED O2: 17.00 %   CALCULATED O2: 16.97 %
ANALYSIS CHECK: F/A IS  .014054 WHEN CALCULATED USING MEASURED O2 VALUE
      --------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
         CONCENTRATION  EMISSIONS INDEX        INSTRUMENT
              PPM        LB/1000 LB FUEL         SOURCE
      --------------------------------------------------------------
       CO    1501.89          125.956             BECKMAN NDIR
      CHX      34.40           11.143             BECKMAN  FID
      --------------------------------------------------------------
       NO       9.63            1.327          AMI  CHEMILUMINESCENCE
      NOX      23.25            3.203          AMI  CHEMILUMINESCENCE
      --------------------------------------------------------------
       NO      12.32            1.697             BECKMAN NDIR
      NOX      26.51            3.652         BECKMAN  [NDIR + NDUV]
      --------------------------------------------------------------
         ABSOLUTE HUMIDITY =   .00 GRAINS PER POUND OF DRY AIR
               SMOKE NUMBER = 11.37
 ALL PILOT.
```

Figure 90. Modified Conventional Liner No. 10 Rig Data at Operational Idle and 50% Open Geometry.

```
        COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG P/U 174, TEST SERIES -A  , READING #  1803
     MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C. JP-4.
TEST DATE: 174                                TIME OF DAY: 1807: 2 HOURS

CYCLE POINT  3    VARIABLE GEOMETRY  50 % CLOSED         25% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          2.145 LB/SEC     AVG BURNER INLET TEMP   375. DEG F
AVG BURNER INLET PRES  59.2   PSIA      AVG BURNER OUTLET TEMP 1365. DEG F
AVG BURNER DELTA P      4.84    "HG      PRESSURE LOSS             4.01 %
OVERALL F/A RATIO      .01367  (F/M)     FUEL FLOW RATE          105.59 LB/HR
AIR LOAD FACTOR        1.0466            PATTERN FACTOR          .22921
BOT HOT SPOT:  # 22 = 1592.  DEG F      MAX BOT / AVG BOT       1.1563
FUEL INLET TEMPERATURE  66.  DEG F      FUEL INLET PRESSURE       58.4  PSIA
HEAT LOADING PARAMETER   .49228E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************* BURNER OUTLET TEMPERATURE SURVEY *******************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1590. 24 1387. 27 1204. 30 1456. 33 1499. 36 1429. 39 1270.
ANNULUS 2 22 1592. 25 1420. 28 1294. 31 1477. 34 1470. 37 1154. 40 1452.
ANNULUS 3 23 1364. 26 1112. 29 1226. 32 1369. 35 1360. 38 1254. 41 1292.

 LEFT SIDE ************* AIR INLET TUBE CONDITIONS ************* RIGHT SIDE
TOTAL PRESSURE           59.25   PSIA    TOTAL PRESSURE           59.14   PSIA
AIR TEMPERATURE           375.  DEG F    AIR TEMPERATURE           375.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................  58.73   PSIA

AIR FLOW DATA: P-REF= 115.2 PSIA   DELTA P= 1.74 "HG    T-REF=  37. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       381.     HZ     VOLUMETRIC FLOW RATE  16.66 GAL/HR
FUEL PRESSURE AT F/M  510.0   PSIA      FUEL TEMP AT F/M           62.  DEG F
--------------------------------------------------------------------------
                     SKIN TEMPERATURE SURVEY:
 #44=  819. DEG F  #45=  772. DEG F  #46=  740. DEG F  #47=   60. DEG F
 #48=  759. DEG F  #
--------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .016233    COMBUSTION EFFICIENCY:  99.3300 %
 MEASURED CO2: 3.365 %   MEASURED O2: 16.40 %   CALCULATED O2: 16.27 %
ANALYSIS CHECK: F/A IS  .016138 WHEN CALCULATED USING MEASURED O2 VALUE
      -------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
         CONCENTRATION  EMISSIONS INDEX       INSTRUMENT
              PPM        LB/1000 LB FUEL         SOURCE
      -------------------------------------------------------------
       CO     465.21          33.346           BECKMAN NDIR
      CHX       9.10           1.027           BECKMAN  FID
      -------------------------------------------------------------
       NO      23.36           2.750       AMI  CHEMILUMINESCENCE
      NOX      38.51           4.534       AMI  CHEMILUMINESCENCE
      -------------------------------------------------------------
       NO      21.84           2.571           BECKMAN NDIR
      NOX      37.97           4.471        BECKMAN  (NDIR + NDUV)
      -------------------------------------------------------------
        ABSOLUTE HUMIDITY =    .00 GRAINS PER POUND OF DRY AIR
             SMOKE NUMBER =   8.41
 PILOT WF= 59.7 LB/HOUR.
```


Figure 91. Modified Conventional Liner No. 10 Rig Data at 25% Power and 50% Open Geometry.

```
        COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A   , READING #  1804
        MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C. JP-4.
TEST DATE: 174                                  TIME OF DAY: 1819:18 HOURS

CYCLE POINT  3   VARIABLE GEOMETRY   0 % CLOSED         25% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          2.152 LB/SEC    AVG BURNER INLET TEMP   374. DEG F
AVG BURNER INLET PRES  59.5    PSIA     AVG BURNER OUTLET TEMP 1367. DEG F
AVG BURNER DELTA P      4.58    "HG      PRESSURE LOSS              3.78 %
OVERALL F/A RATIO      .01371  (F/M)     FUEL FLOW RATE           106.20 LB/HR
AIR LOAD FACTOR        1.0441            PATTERN FACTOR           .23466
BOT HOT SPOT:  # 21 = 1600.  DEG F       MAX BOT / AVG BOT        1.1704
FUEL INLET TEMPERATURE  65.  DEG F       FUEL INLET PRESSURE        58.7  PSIA
HEAT LOADING PARAMETER  .49244E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
          ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1600. 24 1252. 27 1075. 30 1543. 33 1406. 36 1266. 39 1301.
ANNULUS 2 22 1454. 25 1371. 28 1335. 31 1530. 34 1501. 37 1211. 40 1533.
ANNULUS 3 23 1335. 26 1243. 29 1316. 32 1446. 35 1192. 38 1443. 41 1387.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE            59.48   PSIA    TOTAL PRESSURE           59.57   PSIA
AIR TEMPERATURE           374.   DEG F    AIR TEMPERATURE           374.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE......................  58.87   PSIA

AIR FLOW DATA: P-REF= 115.0 PSIA    DELTA P= 1.75 "HG    T-REF=  35. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       333.       HZ     VOLUMETRIC FLOW RATE  16.75 GAL/HR
FUEL PRESSURE AT F/M   513.6    PSIA     FUEL TEMP AT F/M            61.  DEG F
-------------------------------------------------------------------------
                     SKIN TEMPERATURE SURVEY:
 #44=  701. DEG F  #45=  799. DEG F  #46=  758. DEG F  #47=   58. DEG F
 #48=  680. DEG F   #
-------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .015865     COMBUSTION EFFICIENCY:  99.6763 %
 MEASURED CO2: 3.313 %   MEASURED O2: 16.40 %   CALCULATED O2: 16.37 %
ANALYSIS CHECK: F/A IS  .015841 WHEN CALCULATED USING MEASURED O2 VALUE
      ---------------------------------------------------------------
                      EMISSIONS MEASUREMENTS
          CONCENTRATION  EMISSIONS INDEX          INSTRUMENT
              PPM        LB/1000 LB FUEL            SOURCE
      ---------------------------------------------------------------
       CO      214.13          15.311              BECKMAN NDIR
      CHX        3.31            .372              BECKMAN  FID
      ---------------------------------------------------------------
       NO       33.45           3.929        AMI  CHEMILUMINESCENCE
      NOX       41.50           4.874        AMI  CHEMILUMINESCENCE
      ---------------------------------------------------------------
       NO       30.52           3.584              BECKMAN NDIR
      NOX       41.54           4.878        BECKMAN  [NDIR + NDUV]
      ---------------------------------------------------------------
         ABSOLUTE HUMIDITY =   .00 GRAINS PER POUND OF DRY AIR
                SMOKE NUMBER =  7.65
 PILOT WF= 59.8 LB/HOUR.
```

Figure 92. Modified Conventional Liner No. 10 Rig Data at 25% Power and 100% Open Geometry.

```
         COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A  , READING #  1805
       MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C. JP-4.
TEST DATE: 174                                TIME OF DAY: 1835:10 HOURS

CYCLE POINT  4   VARIABLE GEOMETRY   0 % CLOSED        40% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW        2.454 LB/SEC    AVG BURNER INLET TEMP   425. DEG F
AVG BURNER INLET PRES  70.4   PSIA     AVG BURNER OUTLET TEMP 1506. DEG F
AVG BURNER DELTA P      5.50   "HG     PRESSURE LOSS            3.84 %
OVERALL F/A RATIO     .01513  (F/M)    FUEL FLOW RATE         134.20 LB/HR
AIR LOAD FACTOR       1.0437           PATTERN FACTOR          .20998
BOT HOT SPOT:  # 40 = 1733.  DEG F     MAX BOT / AVG BOT       1.1508
FUEL INLET TEMPERATURE  67.  DEG F     FUEL INLET PRESSURE      77.0  PSIA
HEAT LOADING PARAMETER  .52596E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************* BURNER OUTLET TEMPERATURE SURVEY *******************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1703. 24 1329. 27 1153. 30 1657. 33 1551. 36 1394. 39 1488.
ANNULUS 2 22 1599. 25 1457. 28 1451. 31 1666. 34 1664. 37 1394. 40 1733.
ANNULUS 3 23 1437. 26 1345. 29 1381. 32 1581. 35 1498. 38 1642. 41 1542.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE           70.44   PSIA   TOTAL PRESSURE          70.40  PSIA
AIR TEMPERATURE           425.  DEG F   AIR TEMPERATURE          424.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................  69.60  PSIA

AIR FLOW DATA: P-REF= 114.8 PSIA   DELTA P= 2.31 "HG    T-REF=  37. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY      484.       HZ    VOLUMETRIC FLOW RATE  21.19 GAL/HR
FUEL PRESSURE AT F/M  503.4   PSIA     FUEL TEMP AT F/M           63.  DEG F
--------------------------------------------------------------------------
                       SKIN TEMPERATURE SURVEY:
 #44=  805. DEG F  #45=  874. DEG F  #46=  855. DEG F  #47=   57. DEG F
 #48=  744. DEG F  #
--------------------------------------------------------------------------
       GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
    CHEMICAL F/A RATIO:  .017161     COMBUSTION EFFICIENCY:  99.8262 %
  MEASURED CO2: 3.601 %   MEASURED O2: 16.10 %   CALCULATED O2: 15.98 %
ANALYSIS CHECK: F/A IS   .017062 WHEN CALCULATED USING MEASURED O2 VALUE
       -----------------------------------------------------------
                     EMISSIONS MEASUREMENTS
          CONCENTRATION  EMISSIONS INDEX          INSTRUMENT
               PPM       LB/1000 LB FUEL            SOURCE

       -----------------------------------------------------------
        CO    116.15            7.537              BECKMAN NDIR
       CHX      1.06             .108              BECKMAN  FID
       -----------------------------------------------------------
        NO     50.71            5.404         AMI   CHEMILUMINESCENCE
       NOX     55.78            5.945         AMI   CHEMILUMINESCENCE
       -----------------------------------------------------------
        NO     48.11            5.127              BECKMAN NDIR
       NOX     56.58            6.030         BECKMAN  [NDIR + NDUV]
       -----------------------------------------------------------
           ABSOLUTE HUMIDITY =   .00 GRAINS PER POUND OF DRY AIR
                 SMOKE NUMBER =  8.05
 PILOT WF= 39.7 LB/HOUR.
```

Figure 93. Modified Conventional Liner No. 10 Rig Data at 40% Power and 100% Open Geometry.

```
       COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A   , READING #  1806
      MODIFIED CONV. LINER P/N EX116292, NOZZLE EX158700. JP-4.
TEST DATE: 174                                 TIME OF DAY: 1847:39 HOURS

CYCLE POINT  4    VARIABLE GEOMETRY  50 % CLOSED          40% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW         2.466 LB/SEC     AVG BURNER INLET TEMP    424. DEG F
AVG BURNER INLET PRES  70.7    PSIA      AVG BURNER OUTLET TEMP 1507. DEG F
AVG BURNER DELTA P      5.96   "HG       PRESSURE LOSS              4.14 %
OVERALL F/A RATIO     .01511  (F/M)      FUEL FLOW RATE           134.13 LB/HR
AIR LOAD FACTOR        1.0365            PATTERN FACTOR           .17558
BOT HOT SPOT:  # 22 = 1697.   DEG F      MAX BOT / AVG BOT        1.1262
FUEL INLET TEMPERATURE  68.   DEG F      FUEL INLET PRESSURE        76.7  PSIA
HEAT LOADING PARAMETER  .52340E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
          ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1659. 24 1485. 27 1307. 30 1584. 33 1638. 36 1579. 39 1438.
ANNULUS 2 22 1697. 25 1543. 28 1403. 31 1651. 34 1610. 37 1352. 40 1667.
ANNULUS 3 23 1492. 26 1251. 29 1340. 32 1525. 35 1539. 38 1438. 41 1444.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE           70.73   PSIA    TOTAL PRESSURE            70.72   PSIA
AIR TEMPERATURE           424.   DEG F   AIR TEMPERATURE            424.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................  69.96   PSIA

AIR FLOW DATA: P-REF= 114.4 PSIA    DELTA P= 2.33 "HG     T-REF=  38. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY        484.      HZ     VOLUMETRIC FLOW RATE  21.19 GAL/HR
FUEL PRESSURE AT F/M  502.8    PSIA      FUEL TEMP AT F/M            64.  DEG F
---------------------------------------------------------------------------
                        SKIN TEMPERATURE SURVEY:
 #44=  929. DEG F  #45=  963. DEG F  #46=  838. DEG F  #47=   59. DEG F
 #48=  841. DEG F  #
---------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
    CHEMICAL F/A RATIO:  .017708    COMBUSTION EFFICIENCY:  99.6949 %
  MEASURED CO2: 3.707 %   MEASURED O2: 16.00 %   CALCULATED O2: 15.82 %
ANALYSIS CHECK: F/A IS  .017559 WHEN CALCULATED USING MEASURED O2 VALUE
      ---------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
            CONCENTRATION  EMISSIONS INDEX         INSTRUMENT
                 PPM       LB/1000 LB FUEL           SOURCE
      ---------------------------------------------------------------
       CO      228.06           14.817            BECKMAN NDIR
      CHX        1.70             .174            BECKMAN  FID
      ---------------------------------------------------------------
       NO       39.13            4.176        AMI  CHEMILUMINESCENCE
      NOX       46.75            5.309        AMI  CHEMILUMINESCENCE
      ---------------------------------------------------------------
       NO       36.45            3.890            BECKMAN NDIR
      NOX       50.65            5.405        BECKMAN  [NDIR + NDUV]
      ---------------------------------------------------------------
          ABSOLUTE HUMIDITY =   .00 GRAINS PER POUND OF DRY AIR
                SMOKE NUMBER =  9.90
 PILOT WF= 40.0 LB/HOUR.
```

Figure 94. Modified Conventional Liner No. 10 Rig Data at 40% Power and 50% Open Geometry.

```
      COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A  , READING #  1807
      MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C. JP-4.
TEST DATE: 174                                  TIME OF DAY: 1901: 7 HOURS

CYCLE POINT  4    VARIABLE GEOMETRY 100 % CLOSED        40% POWER SETTING
************************** EXPERIMENTAL  CONDITIONS **************************
BURNER AIR FLOW          2.462 LB/SEC     AVG BURNER INLET TEMP   424. DEG F
AVG BURNER INLET PRES  70.5    PSIA      AVG BURNER OUTLET TEMP 1413. DEG F
AVG BURNER DELTA P       7.25    "HG      PRESSURE LOSS             5.05 %
OVERALL F/A RATIO      .01508  (F/M)     FUEL FLOW RATE          133.63 LB/HR
AIR LOAD FACTOR        1.0371            PATTERN FACTOR            .20894
BOT HOT SPOT:. # 21 = 1620.  DEG F       MAX BOT / AVG BOT        1.1463
FUEL INLET TEMPERATURE  67.  DEG F       FUEL INLET PRESSURE        75.8  PSIA
HEAT LOADING PARAMETER  .52281E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

********************* BURNER OUTLET TEMPERATURE SURVEY *********************
            ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1620. 24 1441. 27 1349. 30 1617. 33 1610. 36 1508. 39 1396.
ANNULUS 2 22 1560. 25 1388. 28 1260. 31 1597. 34 1483. 37 1275. 40 1493.
ANNULUS 3 23 1366. 26 1173. 29 1229. 32 1252. 35 1400. 38 1352. 41 1311.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE          70.55   PSIA    TOTAL PRESSURE            70.54   PSIA
AIR TEMPERATURE          424.  DEG F    AIR TEMPERATURE            424.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................  69.78   PSIA

AIR FLOW DATA: P-REF= 114.7 PSIA   DELTA P= 2.31 "HG    T-REF=  37. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY        482.      HZ     VOLUMETRIC FLOW RATE  21.10 GAL/HR
FUEL PRESSURE AT F/M  504.9   PSIA     FUEL TEMP AT F/M           63.  DEG F
-----------------------------------------------------------------------------
                     SKIN TEMPERATURE SURVEY:
 #44=  914. DEG F  #45=  781. DEG F  #46=  896. DEG F  #47=   57. DEG F
 #48=  909. DEG F  #
-----------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .015703    COMBUSTION EFFICIENCY:  99.0584 %
 MEASURED CO2: 3.443 %   MEASURED O2: 16.50 %   CALCULATED O2: 16.14 %
ANALYSIS CHECK: F/A IS  .016429 WHEN CALCULATED USING MEASURED O2 VALUE
      ---------------------------------------------------------------
                      EMISSIONS MEASUREMENTS
        CONCENTRATION  EMISSIONS INDEX          INSTRUMENT
             PPM        LB/1000 LB FUEL            SOURCE
      ---------------------------------------------------------------
       CO      694.38          44.543              BECKMAN NDIR
      CHX        9.83           1.007              BECKMAN  FID
      ---------------------------------------------------------------
       NO       15.32           1.638         AMI  CHEMILUMINESCENCE
      NOX       39.56           4.229         AMI  CHEMILUMINESCENCE
      ---------------------------------------------------------------
       NO       19.68           2.103              BECKMAN NDIR
      NOX       46.28           4.947         BECKMAN  (NDIR + NDUV)
      ---------------------------------------------------------------
         ABSOLUTE HUMIDITY =   .00 GRAINS PER POUND OF DRY AIR
              SMOKE NUMBER = 11.45
 PILOT WF= 39.2 LB/HOUR.
```

Figure 95. Modified Conventional Liner No. 10 Rig Data at 40% Power and 0% Open Geometry.

```
      COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG 8/U 174, TEST SERIES -A   , READING #  1808
      MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C, JP-4.
TEST DATE: 174                                   TIME OF DAY: 1920:24 HOURS

CYCLE POINT  5    VARIABLE GEOMETRY 100 % CLOSED          55% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW         2.971 LB/SEC     AVG BURNER INLET TEMP     464. DEG F
AVG BURNER INLET PRES  82.8   PSIA      AVG BURNER OUTLET TEMP 1536. DEG F
AVG BURNER DELTA P      8.72   "HG      PRESSURE LOSS             5.18 %
OVERALL F/A RATIO     .01617  (F/M)     FUEL FLOW RATE          167.08 LB/HR
AIR LOAD FACTOR        1.0537           PATTERN FACTOR          .22467
BOT HOT SPOT:   # 21 = 1777.  DEG F     MAX BOT / AVG BOT       1.1569
FUEL INLET TEMPERATURE  68.   DEG F     FUEL INLET PRESSURE       98.4  PSIA
HEAT LOADING PARAMETER  .55701E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
          ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1777. 24 1566. 27 1447. 30 1730. 33 1719. 36 1613. 39 1502.
ANNULUS 2 22 1710. 25 1588. 28 1379. 31 1706. 34 1613. 37 1372. 40 1626.
ANNULUS 3 23 1530. 26 1251. 29 1342. 32 1539. 35 1483. 38 1447. 41 1391.

 LEFT SIDE ************* AIR INLET TUBE CONDITIONS ************* RIGHT SIDE
TOTAL PRESSURE          82.80   PSIA    TOTAL PRESSURE          82.77   PSIA
AIR TEMPERATURE          464.   DEG F   AIR TEMPERATURE          464.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE........................  81.83   PSIA

AIR FLOW DATA: P-REF= 114.2 PSIA   DELTA P= 3.16 "HG    T-REF=  37. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       634.     HZ     VOLUMETRIC FLOW RATE  26.40 GAL/HR
FUEL PRESSURE AT F/M  487.7   PSIA      FUEL TEMP AT F/M          64.  DEG F
--------------------------------------------------------------------------
                        SKIN TEMPERATURE SURVEY:
#44= 1013. DEG F   #45=  835. DEG F  #46=  914. DEG F   #47=   57. DEG F
#48=  957. DEG F   #
--------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO: .017668     COMBUSTION EFFICIENCY:  99.4763 %
MEASURED CO2: 3.680 %   MEASURED O2: 16.40 %    CALCULATED O2: 15.84 %
ANALYSIS CHECK: F/A IS  .017216 WHEN CALCULATED USING MEASURED O2 VALUE
      ------------------------------------------------------------
                    EMISSIONS MEASUREMENTS
         CONCENTRATION  EMISSIONS INDEX        INSTRUMENT
              PPM       LB/1000 LB FUEL          SOURCE
      ------------------------------------------------------------
      CO     404.22          24.567           BECKMAN NDIR
      CHX      2.49            .238           BECKMAN  FID
      ------------------------------------------------------------
      NO      25.40           2.545       AMI  CHEMILUMINESCENCE
      NOX     48.73           4.865       AMI  CHEMILUMINESCENCE
      ------------------------------------------------------------
      NO      21.90           2.186           BECKMAN NDIR
      NOX     49.88           4.979       BECKMAN  (NDIR + NDUV)
      ------------------------------------------------------------
         ABSOLUTE HUMIDITY =    .00 GRAINS PER POUND OF DRY AIR
              SMOKE NUMBER = 12.35
 PILOT WF= 29.8 LB/HOUR.
```

Figure 96. Modified Conventional Liner No. 10 Rig Data at 55% Power and 0% Open Geometry.

```
         COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A  , READING #  1809
      MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C, JP-4.
TEST DATE: 174                                  TIME OF DAY: 1935:52 HOURS

CYCLE POINT  5   VARIABLE GEOMETRY  50 % CLOSED         55% POWER SETTING
************************* EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          2.862 LB/SEC     AVG BURNER INLET TEMP   463. DEG F
AVG BURNER INLET PRES  82.5   PSIA      AVG BURNER OUTLET TEMP 1620. DEG F
AVG BURNER DELTA P      7.45   "HG      PRESSURE LOSS             4.43 %
OVERALL F/A RATIO      .01624  (F/M)    FUEL FLOW RATE          167.36 LB/HR
AIR LOAD FACTOR        1.0542           PATTERN FACTOR           .20930
BOT HOT SPOT:  # 22 = 1863.  DEG F      MAX BOT / AVG BOT        1.1495
FUEL INLET TEMPERATURE  70.  DEG F      FUEL INLET PRESSURE       98.6  PSIA
HEAT LOADING PARAMETER  .56002E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
            ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1810. 24 1641. 27 1463. 30 1729. 33 1760. 36 1736. 39 1489.
ANNULUS 2 22 1863. 25 1667. 28 1545. 31 1742. 34 1713. 37 1440. 40 1700.
ANNULUS 3 23 1658. 26 1368. 29 1438. 32 1629. 35 1661. 38 1517. 41 1499.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE            82.47   PSIA    TOTAL PRESSURE          82.49   PSIA
AIR TEMPERATURE            464.  DEG F    AIR TEMPERATURE          463.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE......................  81.31    PSIA

AIR FLOW DATA: P-REF= 114.1 PSIA   DELTA P= 3.16 "HG    T-REF=  40. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY        608.      HZ     VOLUMETRIC FLOW RATE  26.49 GAL/HR
FUEL PRESSURE AT F/M  468.4    PSIA     FUEL TEMP AT F/M           67.  DEG F
---------------------------------------------------------------------------
                         SKIN TEMPERATURE SURVEY:
 #44= 1008. DEG F  #45=  919. DEG F  #46=  863. DEG F  #47=   57. DEG F
 #48=  978. DEG F  #
---------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .018529    COMBUSTION EFFICIENCY:  99.8315 %
 MEASURED CO2: 3.894 %   MEASURED O2: 15.60 %   CALCULATED O2: 15.57 %
ANALYSIS CHECK: F/A IS  .018500 WHEN CALCULATED USING MEASURED O2 VALUE
      -------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
          CONCENTRATION  EMISSIONS INDEX        INSTRUMENT
               PPM        LB/1000 LB FUEL          SOURCE

      -------------------------------------------------------------
       CO      123.71          7.484            BECKMAN NDIR
       CHX        .48           .046            BECKMAN  FID
      -------------------------------------------------------------
       NO       49.83          4.951       AMI  CHEMILUMINESCENCE
       NOX      60.02          5.963       AMI  CHEMILUMINESCENCE
      -------------------------------------------------------------
       NO       48.24          4.793            BECKMAN NDIR
       NOX      61.50          6.111        BECKMAN  (NDIR + NDUV)
      -------------------------------------------------------------
         ABSOLUTE HUMIDITY =   .00 GRAINS PER POUND OF DRY AIR
              SMOKE NUMBER =  8.60
 PILOT WF= 30.0 LB/HOUR.
```

Figure 97. Modified Conventional Liner No. 10 Rig Data at 55% Power and 50% Open Geometry.

```
        COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A   , READING #  1810
      MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C, JP-4.
TEST DATE: 174                                 TIME OF DAY: 1947:33 HOURS

CYCLE POINT  5    VARIABLE GEOMETRY    0 % CLOSED        55% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          2.839 LB/SEC    AVG BURNER INLET TEMP   464. DEG F
AVG BURNER INLET PRES   82.6    PSIA     AVG BURNER OUTLET TEMP 1636. DEG F
AVG BURNER DELTA P       6.59    "HG     PRESSURE LOSS             3.92 %
OVERALL F/A RATIO       .01635  (F/M)    FUEL FLOW RATE          167.10 LB/HR
AIR LOAD FACTOR         1.0455           PATTERN FACTOR          .23839
BOT HOT SPOT:  # 21 = 1915.  DEG F       MAX BOT / AVG BOT       1.1707
FUEL INLET TEMPERATURE  70.  DEG F       FUEL INLET PRESSURE       99.4  PSIA
HEAT LOADING PARAMETER  .55865E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 1915. 24 1423. 27 1304. 30 1797. 33 1692. 36 1517. 39 1536.
ANNULUS 2 22 1743. 25 1531. 28 1646. 31 1802. 34 1812. 37 1445. 40 1797.
ANNULUS 3 23 1623. 26 1486. 29 1552. 32 1698. 35 1732. 38 1688. 41 1620.

 LEFT SIDE ************* AIR INLET TUBE CONDITIONS ************* RIGHT SIDE
TOTAL PRESSURE          82.55   PSIA    TOTAL PRESSURE          82.56   PSIA
AIR TEMPERATURE          464.  DEG F    AIR TEMPERATURE          464.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE........................    81.59   PSIA

AIR FLOW DATA: P-REF= 114.1 PSIA   DELTA P= 3.11 "HG    T-REF=  39. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY        685.     HZ    VOLUMETRIC FLOW RATE  26.45 GAL/HR
FUEL PRESSURE AT F/M  499.3   PSIA      FUEL TEMP AT F/M          67.  DEG F
--------------------------------------------------------------------------
                        SKIN TEMPERATURE SURVEY:
 #44=  883. DEG F  #45=  944. DEG F  #46=  892. DEG F  #47=   58. DEG F
 #48=  786. DEG F  *
--------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .018006     COMBUSTION EFFICIENCY:  99.8853 %
 MEASURED CO2: 3.787 %   MEASURED O2: 15.60 %   CALCULATED O2: 15.72 %
ANALYSIS CHECK: F/A IS  .018108 WHEN CALCULATED USING MEASURED O2 VALUE
      ------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
         CONCENTRATION  EMISSIONS INDEX      INSTRUMENT
              PPM       LB/1000 LB FUEL        SOURCE
      ------------------------------------------------------------
       CO     72.54          4.360            BECKMAN NDIR
      CHX       .33           .031            BECKMAN  FID
      ------------------------------------------------------------
       NO     60.97          6.020        AMI  CHEMILUMINESCENCE
      NOX     70.22          6.933        AMI  CHEMILUMINESCENCE
      ------------------------------------------------------------
       NO     59.32          5.857            BECKMAN NDIR
      NOX     69.91          6.903        BECKMAN  (NDIR + NDUV)
      ------------------------------------------------------------
         ABSOLUTE HUMIDITY =  .00 GRAINS PER POUND OF DRY AIR
              SMOKE NUMBER =  9.51
PILOT WF= 30.0 LB/HOUR.
```

Figure 98. Modified Conventional Liner No. 10 Rig Data at 55% Power and 100% Open Geometry.

```
         COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A  , READING #  1811
     MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C. JP-4.
TEST DATE: 174                                   TIME OF DAY: 2014: 6 HOURS

CYCLE POINT  6   VARIABLE GEOMETRY  50 % CLOSED          75% POWER SETTING
************************* EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          3.087 LB/SEC     AVG BURNER INLET TEMP   517. DEG F
AVG BURNER INLET PRES  94.0    PSIA       AVG BURNER OUTLET TEMP 1810. DEG F
AVG BURNER DELTA P      8.30    "HG       PRESSURE LOSS             4.34 %
OVERALL F/A RATIO      .01890  (F/M)      FUEL FLOW RATE          209.99 LB/HR
AIR LOAD FACTOR        1.0262             PATTERN FACTOR          .19900
BOT HOT SPOT:  # 21 = 2067.  DEG F        MAX BOT / AVG BOT       1.1422
FUEL INLET TEMPERATURE  71.  DEG F        FUEL INLET PRESSURE     129.5  PSIA
HEAT LOADING PARAMETER  .61659E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
            ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 2067. 24 1722. 27 1629. 30 1899. 33 1959. 36 1916. 39 1702.
ANNULUS 2 22 2058. 25 1759. 28 1713. 31 1918. 34 1870. 37 1600. 40 1997.
ANNULUS 3 23 1825. 26 1563. 29 1634. 32 1757. 35 1902. 38 1742. 41 1770.

 LEFT SIDE ************* AIR INLET TUBE CONDITIONS ************* RIGHT SIDE
TOTAL PRESSURE           93.97    PSIA    TOTAL PRESSURE             94.02   PSIA
AIR TEMPERATURE          517.    DEG F    AIR TEMPERATURE            517.   DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.....................  92.63   PSIA

AIR FLOW DATA: P-REF= 113.7 PSIA   DELTA P= 3.70 "HG    T-REF=  40. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       765.       HZ    VOLUMETRIC FLOW RATE  33.29 GAL/HR
FUEL PRESSURE AT F/M  349.5    PSIA       FUEL TEMP AT F/M             69.  DEG F
--------------------------------------------------------------------------
                          SKIN TEMPERATURE SURVEY:
 #44= 1139. DEG F  #45= 1348. DEG F  #46=  986. DEG F  #47=   61. DEG F
 #48= 1022. DEG F  #
--------------------------------------------------------------------------
       GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
    CHEMICAL F/A RATIO:  .020895     COMBUSTION EFFICIENCY:  99.9261 %
 MEASURED CO2: 4.412 %    MEASURED O2: 14.80 %    CALCULATED O2: 14.85 %
ANALYSIS CHECK: F/A IS   .020946 WHEN CALCULATED USING MEASURED O2 VALUE
      ----------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
           CONCENTRATION  EMISSIONS INDEX          INSTRUMENT
                PPM        LB/1000 LB FUEL            SOURCE
      ----------------------------------------------------------------
       CO     40.66           2.120              BECKMAN NDIR
      CHX      .40             .033              BECKMAN  FID
      ----------------------------------------------------------------
       NO     87.48           7.491          AMI  CHEMILUMINESCENCE
      NOX     88.55           7.582          AMI  CHEMILUMINESCENCE
      ----------------------------------------------------------------
       NO     83.64           7.161              BECKMAN NDIR
      NOX     92.53           7.923         BECKMAN  (NDIR + NDUV)
      ----------------------------------------------------------------
         ABSOLUTE HUMIDITY =   .00 GRAINS PER POUND OF DRY AIR
                 SMOKE NUMBER =  5.10
 PILOT WF= 20.0 LB/HOUR.
```

Figure 99. Modified Conventional Liner No. 10 Rig Data at 75% Power and 50% Open Geometry.

```
        COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A   , READING #  1812
       MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C, JP-4.
TEST DATE: 174                                 TIME OF DAY: 2032:13 HOURS

CYCLE POINT  6    VARIABLE GEOMETRY 100 % CLOSED         75% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          3.124 LB/SEC     AVG BURNER INLET TEMP    516. DEG F
AVG BURNER INLET PRES  94.2  PSIA         AVG BURNER OUTLET TEMP 1737. DEG F
AVG BURNER DELTA P     10.17  "HG         PRESSURE LOSS             5.30 %
OVERALL F/A RATIO      .01873  (F/M)      FUEL FLOW RATE          210.57 LB/HR
AIR LOAD FACTOR        1.0360             PATTERN FACTOR           .25013
BOT HOT SPOT:  # 21 = 2043.   DEG F       MAX BOT / AVG BOT        1.1758
FUEL INLET TEMPERATURE  72.  DEG F        FUEL INLET PRESSURE      129.1  PSIA
HEAT LOADING PARAMETER  .61707E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************* BURNER OUTLET TEMPERATURE SURVEY *******************
          ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 2043. 24 1775. 27 1659. 30 1951. 33 1901. 36 1810. 39 1702.
ANNULUS 2 22 1981. 25 1719. 28 1576. 31 1902. 34 1783. 37 1543. 40 1849.
ANNULUS 3 23 1762. 26 1429. 29 1561. 32 1643. 35 1684. 38 1645. 41 1565.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE          94.18  PSIA     TOTAL PRESSURE          94.18   PSIA
AIR TEMPERATURE          517.  DEG F    AIR TEMPERATURE          516.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................  92.57    PSIA

AIR FLOW DATA: P-REF= 113.8 PSIA    DELTA P= 3.77 "HG    T-REF=  38. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY      767.      HZ      VOLUMETRIC FLOW RATE  33.37 GAL/HR
FUEL PRESSURE AT F/M   352.6     PSIA     FUEL TEMP AT F/M         69.  DEG F
-------------------------------------------------------------------------
                         SKIN TEMPERATURE SURVEY:
#44= 1128. DEG F  #45=  939. DEG F  #46= 1010. DEG F  #47=   59. DEG F
#48= 1083. DEG F  #
-------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .019660     COMBUSTION EFFICIENCY:  99.8186 %
 MEASURED CO2: 4.137 %   MEASURED O2: 15.30 %   CALCULATED O2: 15.23 %
ANALYSIS CHECK: F/A IS  .019601 WHEN CALCULATED USING MEASURED O2 VALUE
     ------------------------------------------------------------
                         EMISSIONS MEASUREMENTS
         CONCENTRATION  EMISSIONS INDEX       INSTRUMENT
              PPM       LB/1000 LB FUEL         SOURCE
     ------------------------------------------------------------
      CO     139.04          7.313            BECKMAN NDIR
     CHX       1.04           .086            BECKMAN  FID
     ------------------------------------------------------------
      NO      61.18          5.286        AMI  CHEMILUMINESCENCE
     NOX      67.36          5.819        AMI  CHEMILUMINESCENCE
     ------------------------------------------------------------
      NO      55.04          4.755            BECKMAN NDIR
     NOX      70.68          6.106        BECKMAN  (NDIR + NOUV)
     ------------------------------------------------------------
          ABSOLUTE HUMIDITY =    .00 GRAINS PER POUND OF DRY AIR
                SMOKE NUMBER =   0.60
PILOT WF= 20.2 LB/HOUR.
```

Figure 100. Modified Conventional Liner No. 10 Rig Data at 75% Power and 0% Open Geometry.

```
         COMBUSTION RESEARCH LABORATORY - FEASIBILITY RIG EXPERIMENTS
T63 TYPE COMBUSTOR TEST - RIG B/U 174, TEST SERIES -A  , READING #  1813
     MODIFIED CONV. LINER P/N EX116292, NOZZLE EX15870C, JP-4.
TEST DATE: 174                                  TIME OF DAY: 2055:27 HOURS

CYCLE POINT  7    VARIABLE GEOMETRY 100 % CLOSED       100% POWER SETTING
************************ EXPERIMENTAL  CONDITIONS ************************
BURNER AIR FLOW          3.317 LB/SEC    AVG BURNER INLET TEMP    569. DEG F
AVG BURNER INLET PRES 105.2    PSIA    AVG BURNER OUTLET TEMP 1966. DEG F
AVG BURNER DELTA P     10.71    "HG    PRESSURE LOSS              5.00 %
OVERALL F/A RATIO      .02186  (F/M)    FUEL FLOW RATE          260.95 LB/HR
AIR LOAD FACTOR        1.0115          PATTERN FACTOR           .25340
BOT HOT SPOT:  # 21 = 2320.  DEG F     MAX BOT / AVG BOT        1.1800
FUEL INLET TEMPERATURE  74.  DEG F     FUEL INLET PRESSURE      163.9  PSIA
HEAT LOADING PARAMETER  .68475E+06 BTU/HOUR/ATM/CUBIC FOOT (V= 1.000000)

******************** BURNER OUTLET TEMPERATURE SURVEY ********************
           ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP  ID TEMP
ANNULUS 1 21 2320. 24 1956. 27 1856. 30 2199. 33 2145. 36 2029. 39 1938.
ANNULUS 2 22 2237. 25 1892. 28 1845. 31 2113. 34 2022. 37 1787. 40 2107.
ANNULUS 3 23 1999. 26 1581. 29 1810. 32 1867. 35 1894. 38 1881. 41 1802.

 LEFT SIDE ************ AIR INLET TUBE CONDITIONS ************ RIGHT SIDE
TOTAL PRESSURE          105.15   PSIA   TOTAL PRESSURE          105.21   PSIA
AIR TEMPERATURE          570.   DEG F   AIR TEMPERATURE          569.  DEG F
COMBUSTOR OUTER CASE STATIC PRESSURE.......................... 103.38   PSIA

AIR FLOW DATA: P-REF= 113.5 PSIA   DELTA P= 4.27 "HG   T-REF=  38. DEG F
FUEL SYSTEM DATA:
FUEL F/M FREQUENCY       953.       HZ    VOLUMETRIC FLOW RATE  41.40 GAL/HR
FUEL PRESSURE AT F/M  327.6   PSIA    FUEL TEMP AT F/M           71.  DEG F
--------------------------------------------------------------------------
                        SKIN TEMPERATURE SURVEY:
 #44= 1283. DEG F  #45= 1055. DEG F  #46= 1143. DEG F  #47=    64. DEG F
 #48= 1211. DEG F  *
--------------------------------------------------------------------------
      GAS ANALYSIS DATA FOR GAS SAMPLES TAKEN IN THE EXHAUST DUCT
   CHEMICAL F/A RATIO:  .022706    COMBUSTION EFFICIENCY:  99.9355 %
 MEASURED CO2: 4.804 %   MEASURED O2: 14.30 %   CALCULATED O2: 14.31 %
ANALYSIS CHECK: F/A IS  .022713 WHEN CALCULATED USING MEASURED O2 VALUE
      ------------------------------------------------------------
                        EMISSIONS MEASUREMENTS
         CONCENTRATION  EMISSIONS INDEX          INSTRUMENT
              PPM        LB/1000 LB FUEL           SOURCE
      ------------------------------------------------------------
       CO        33.31             1.506            BECKMAN NDIR
      CHX          .73              .052            BECKMAN  FID
      ------------------------------------------------------------
       NO        97.54             7.243        AMI  CHEMILUMINESCENCE
      NOX        98.64             7.324        AMI  CHEMILUMINESCENCE
      ------------------------------------------------------------
       NO        94.50             7.016            BECKMAN NDIR
      NOX       102.56             7.615        BECKMAN  [NDIR + NDUV]
      ------------------------------------------------------------
          ABSOLUTE HUMIDITY =    .00 GRAINS PER POUND OF DRY AIR
                SMOKE NUMBER =  4.23
 PILOT WF= 20.0 LB/HOUR.
```

Figure 101. Modified Conventional Liner No. 10 Rig Data at 100% Power and 0% Open Geometry.

TABLE 68. COMBUSTION SYSTEM PERFORMANCE OF MODIFIED CONVENTIONAL LINER NO. 10 HAVING VARIABLE DILUTION GEOMETRY AND USING DDA AIRBLAST FUEL NOZZLE (EX-115870C) WITH SCHEDULED PILOT FLOWS AT MODEL 250-C20B ENGINE CONDITIONS

	Opr'l Idle	Percent Power 25	40	55	75	100
Pilot Flow Rate (lb/hr)	70	60	40	30	20	20
I. 100% Dilution Hole Area						
A. Emissions						
CO (ppm)	635.0	214.1	116.2	72.5		
C_3H_8 (ppm)	30.8	3.3	1.1	.3		
NO_x (ppm NO_2)	26.2	41.5	55.8	70.2		
Smoke Number	8.6	7.6	8.0	9.5		
CO_2 (%)	2.55	3.31	3.60	3.79		
B. Gas Analysis						
Comb. Eff. (%)	98.61	99.68	99.83	99.89		
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.078	1.157	1.134	1.101		
C. System Performance						
Pressure Drop (%)	3.39	3.78	3.84	3.92		
T_{max}/T_{avg} (°F/°F)	1.153	1.170	1.151	1.171		
Pattern Factor	.2056	.2347	.2100	.2384		
II. 50% Dilution Hole Area						
A. Emissions						
CO (ppm)	1501.9	465.2	228.1	123.7	40.7	
C_3H_8 (ppm)	84.4	9.1	1.7	.5	.4	
NO_x (ppm NO_2)	23.2	38.5	49.8	60.0	88.6	
Smoke Number	11.4	8.4	9.9	8.6	5.1	
CO_2 (%)	2.80	3.36	3.71	3.89	4.41	
B. Gas Analysis						
Comb. Eff. (%)	97.61	99.33	99.69	99.83	99.93	
$F\text{-}A_{chem}/F\text{-}A_{mech}$	1.207	1.187	1.172	1.141	1.106	
C. System Performance						
Pressure Drop (%)	4.16	4.01	4.14	4.43	4.34	
T_{max}/T_{avg} (°F/°F)	1.191	1.166	1.126	1.150	1.142	
Pattern Factor	.2597	.2292	.1756	.2093	.1990	
III. 0% Dilution Hole Area						
A. Emissions						
CO (ppm)			684.4	404.2	139.0	33.3
C_3H_8 (ppm)			9.8	2.5	1.0	.7
NO_x (ppm NO_2)			39.6	48.7	67.4	98.6
Smoke Number			11.4	12.4	8.6	4.2
CO_2 (%)			3.44	3.68	4.14	4.80
B. Gas Analysis						
Comb. Eff. (%)			99.06	99.48	99.82	99.94
$F\text{-}A_{chem}/F\text{-}A_{mech}$			1.108	1.093	1.050	1.039
C. System Performance						
Pressure Drop (%)			5.05	5.18	5.30	5.00
T_{max}/T_{avg} (°F/°F)			1.146	1.157	1.176	1.180
Pattern Factor			.2089	.2247	.2501	.2534

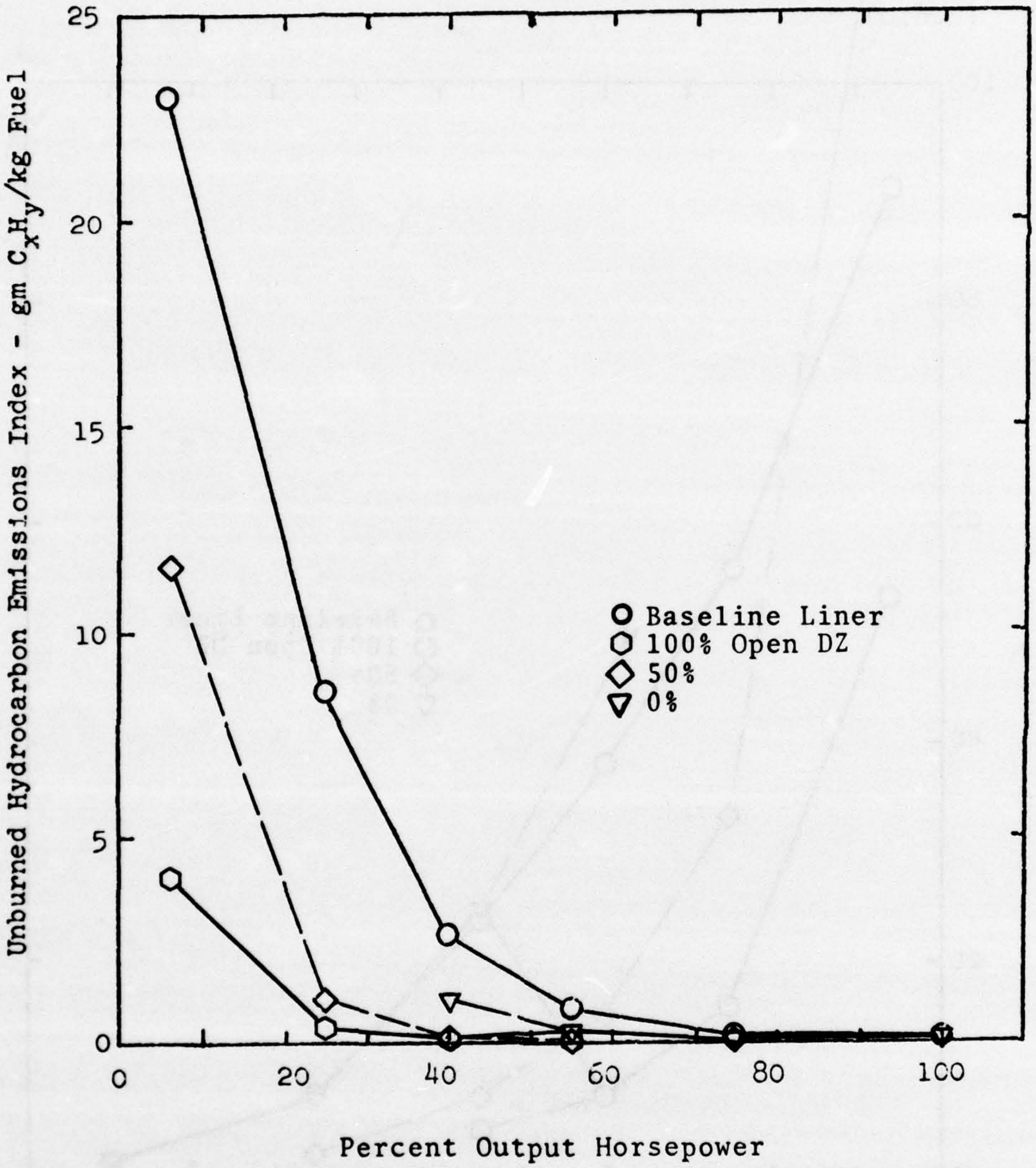


Figure 102. Modified Conventional Liner No. 10 and Baseline Liner Unburned Hydrocarbon Emissions.

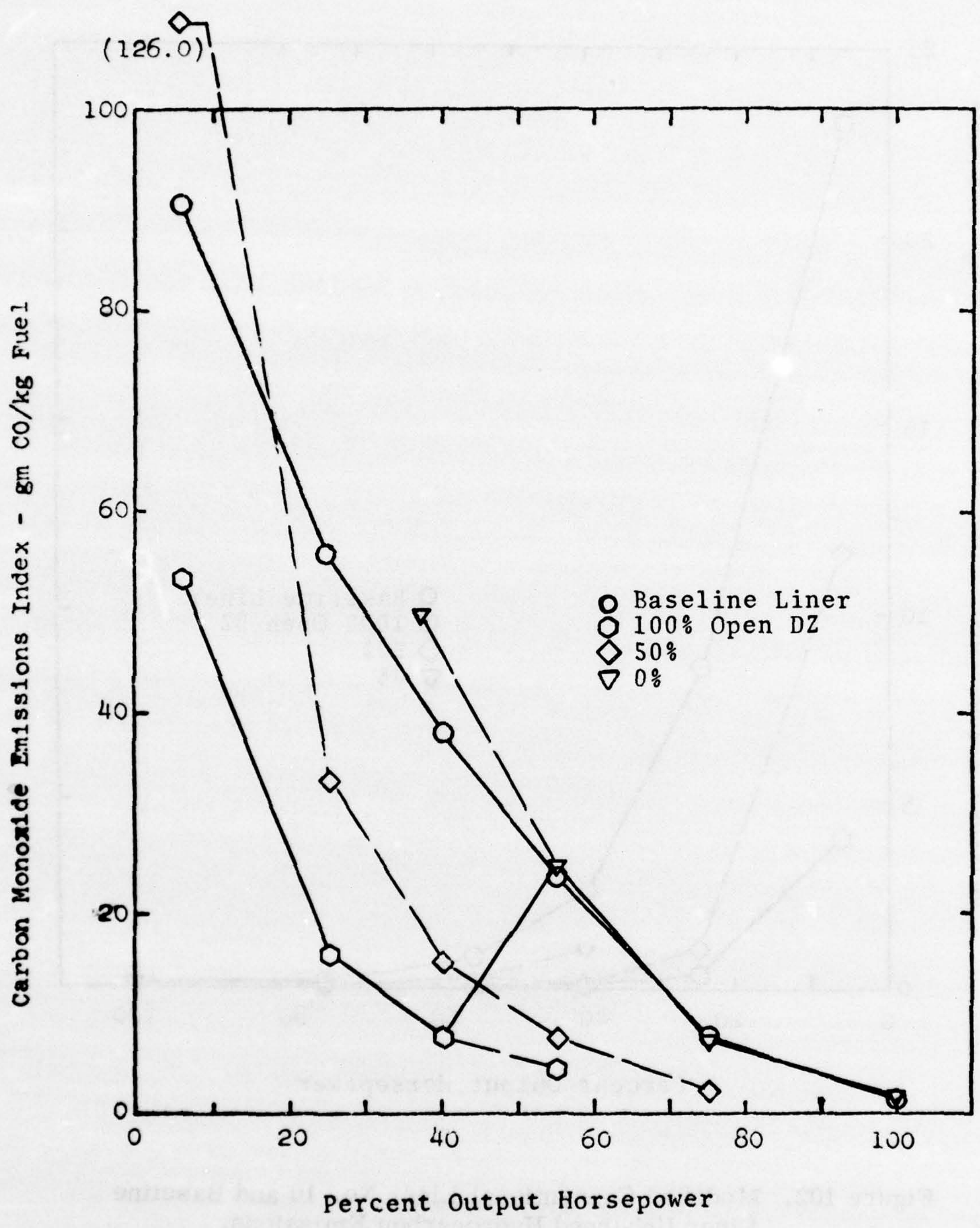


Figure 103. Modified Conventional Liner No. 10 and Baseline Liner Carbon Monoxide.

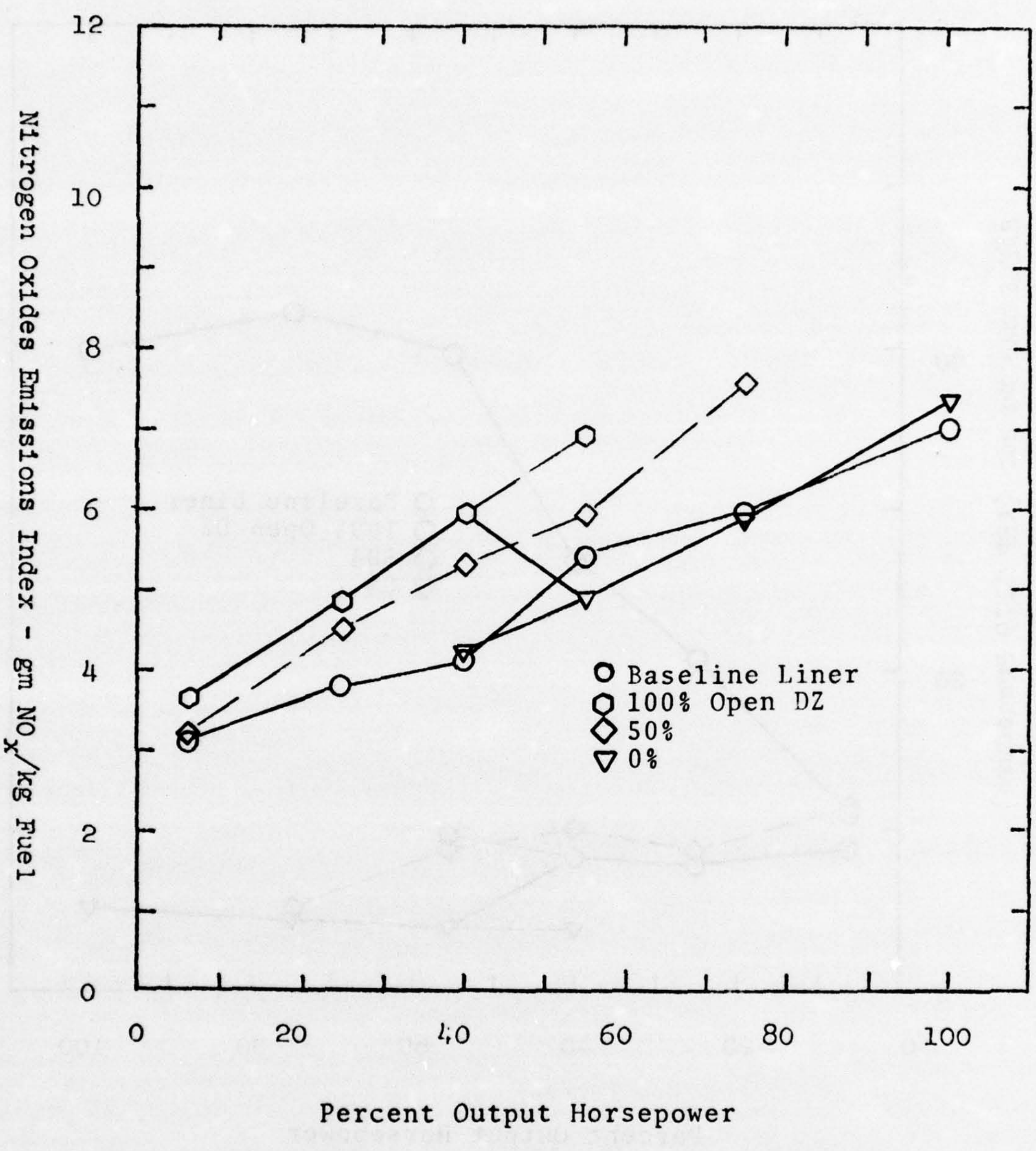


Figure 104. Modified Conventional Liner No. 10 and Baseline Liner Total Nitrogen Oxides.

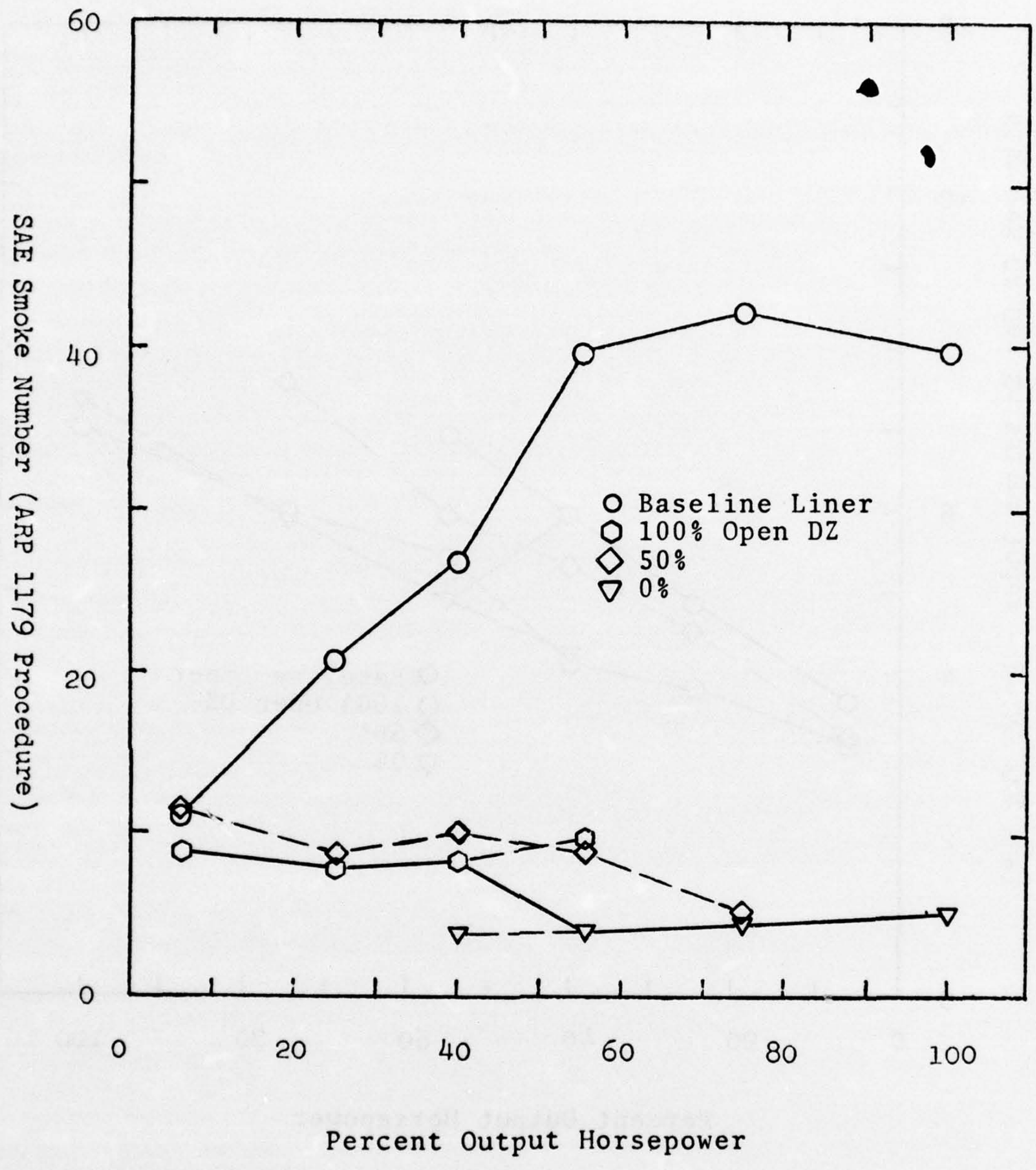


Figure 105. Modified Conventional Liner No. 10 and Baseline Liner Exhaust Smoke Emissions.

Because only three dilution hole areas were used in the actual testing, the exhaust emissions for CH_x, CO, and NO_x were plotted as functions of the percent dilution hole setting in Figures 106, 107, and 108. The curves in each of these plots correspond to the LOH duty cycle power levels from operational idle to 100% power. Using these curves, exhaust emissions concentrations for additional dilution hole area settings were obtained for 20, 30, 40, 60, and 75% open. Using this matrix of data, combinations of settings were searched to establish minimum total duty cycle emissions for a given set of both emissions levels and operational constraints. These minimum emissions results are presented in Table 69 for modified conventional liner No. 10. The primary zone could not be leaned to the point where the 90% baseline NO_x goal could be achieved. Holding cycle NO_x at baseline levels was achievable with this design. Only by allowing the NO_x to increase above baseline levels to allow trading NO_x for CO reductions could the 50% baseline in total emissions be obtained. The dilution settings accompanying the emissions results in Table 69 are presented in Table 70.

LOH duty cycle summaries for two-position dilution geometry control are shown in Table 71 for emission levels using only the actually-measured rig test data, and for the expanded data matrix. To achieve no NO_x increase above baseline, the actual data using 100% open through 40% power and 0% open above 40% power was the minimum total emissions configuration. The next best two-position dilution geometry combination was the 75% open setting from the expanded data set (see the lower part of Table 71). Baseline NO_x could be maintained, but the total emissions increased due to the rise in CH_x and CO.

Exhaust temperature patterns for modified conventional liner No. 10 are compared with baseline pattern factors in Figure 109. For the minimum emissions combination of settings, the exhaust profile is satisfactory for a preliminary engine run. Individual temperatures in the exhaust annulus at 100% power are indicated in Figure 110 for the 0% dilution setting.

Four liner metal temperature thermocouple readings are plotted in Figure 111 for the minimum emissions combination of dilution area settings. The fifth thermocouple, at the reaction zone, was destroyed during fabrication. All measured temperatures were well below the 1700°F maximum allowable goal for good durability. The highest temperatures measured were at the liner exhaust seal ring, and here no thermocouple read as high as 1300°F.

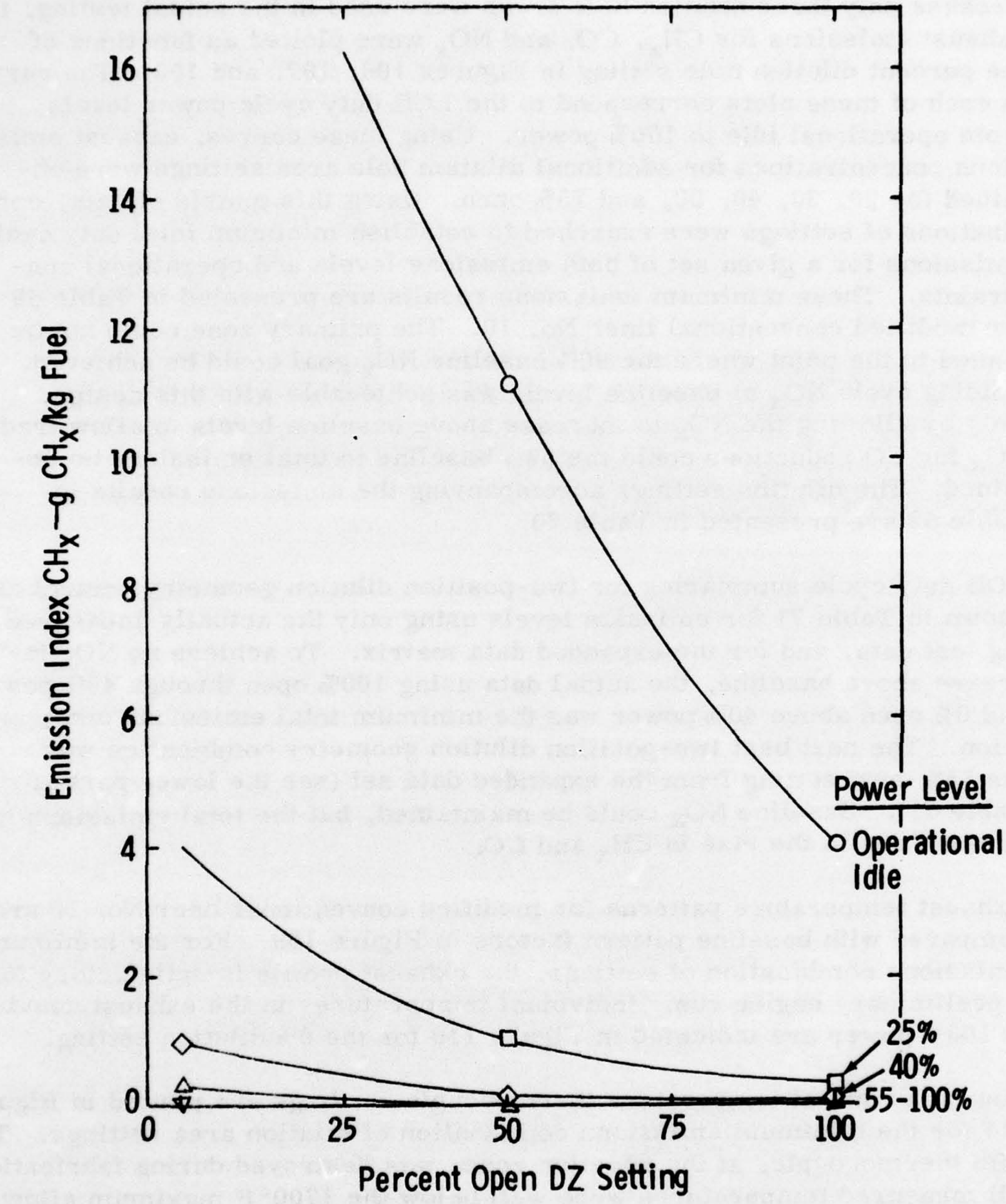


Figure 106. Modified Conventional Liner No. 10 Interpolated Unburned Hydrocarbon Curves.

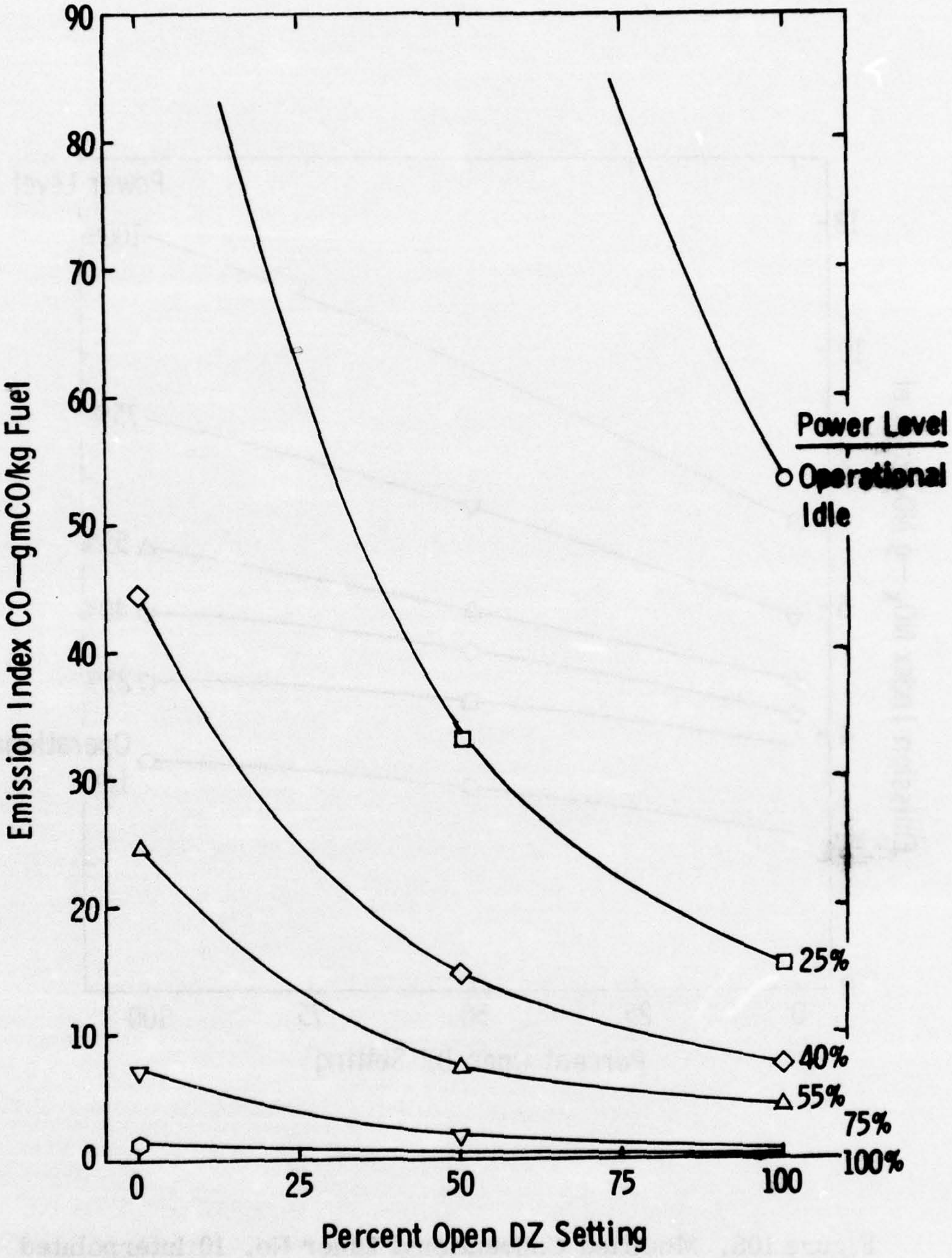


Figure 107. Modified Conventional Liner No. 10 Interpolated Carbon Monoxide Curves.

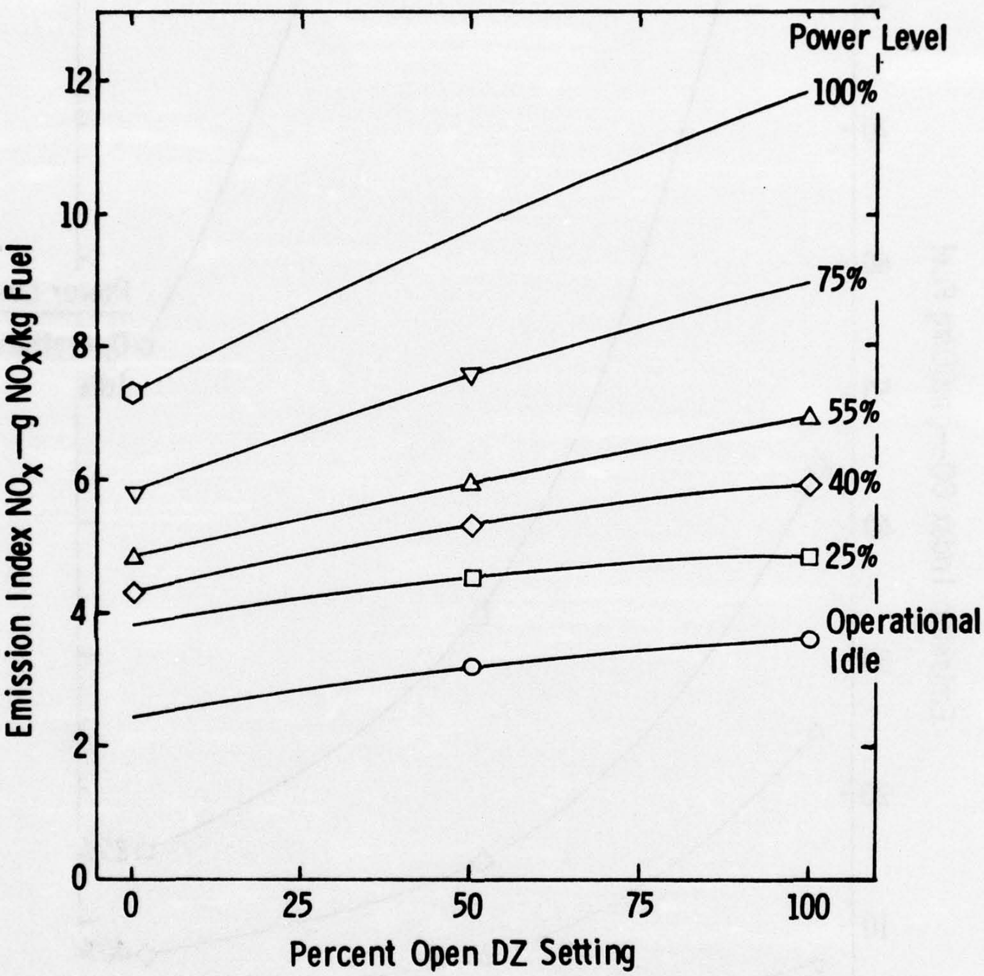


Figure 108. Modified Conventional Liner No. 10 Interpolated Total Nitrogen Oxides Curves.

TABLE 69. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS INDEX SUMMARY FOR BASELINE AND LOW-EMISSIONS VARIABLE-GEOMETRY MODIFIED-CONVENTIONAL COMBUSTORS USING TEST RIG DATA.

Combustor Liner	Emissions Index (gm/kg Fuel) C_xH_y	CO	NO_x	Total
Model 250-C20B Baseline	2.287	23.955	5.396	31.639
Modified Conventional EX-116292 (NO. 10)				
I. Multiple Dilution Settings				
A. Meeting 90% NO_x	--	--	--	--
B. Meeting 100% NO_x	.417 18%	17.936 75%	5.367 99%	23.271 75%
C. Minimum Total	.306 13%	7.061 29%	6.871 127%	14.239 45%
II. Two Dilution Settings				
A. Meeting 90% NO_x	--	--	--	--
B. Meeting 100% NO_x	.417 18%	17.936 75%	5.367 99%	23.721 75%
C. Minimum Total	.306 13%	6.852 29%	7.145 132%	14.304 45%

TABLE 70. DILUTION HOLE AREA SETTINGS FOR LOW-EMISSIONS VARIABLE-GEOMETRY MODIFIED-CONVENTIONAL COMBUSTOR AT LOH DUTY CYCLE CONDITIONS.

Combustor Liner	Dilution Hole Areas at LOH Power Levels				
	Idle	40%	55%	75%	100%
Modified Conventional EX-116292 (No. 10)					
I. Multiple Dilution Settings					
A. Meeting 90% NO_x	--	--	--	--	--
B. Meeting 100% NO_x	100	100	0	0	0
C. Minimum Total	100	100	100	60	0
II. Two Dilution Settings					
A. Meeting 90% NO_x	--	--	--	--	--
B. Meeting 100% NO_x	100	100	0	0	0
C. Minimum Total	100	100	100	100	0

TABLE 71. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FOR MODIFIED CONVENTIONAL LINER NO. 10

MODIFIED CONVENTIONAL NO.10, EX-116292,NOZZLE EX-115870C, 2-POSITION ACT 2-12-75

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1800.	0.15	70.17	4.070	53.334	3.618	61.022	8.61
1804.	0.00	106.20	0.372	15.311	4.847	20.530	7.65
1805.	0.15	134.20	0.108	7.537	5.945	13.590	8.05
1808.	0.45	167.08	0.238	24.567	4.865	29.670	12.35
1812.	0.20	210.57	0.086	7.313	5.819	13.218	8.60
1813.	0.05	260.95	0.052	1.506	7.324	8.882	4.23
CYCLE TOTALS		161.00	0.417	17.936	5.367	23.721	12.35
PERCENT OF BASELINE		100.59	18.25	74.87	99.45	74.97	

MODIFIED CONVENTIONAL NO.10, EX-116292,NOZZLE EX-115870C, 2-POSITION INT 2-12-75

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1800.	0.15	70.17	4.070	53.334	3.618	61.022	8.61
1804.	0.00	106.20	0.372	15.311	4.847	20.530	7.65
1805.	0.15	134.20	0.108	7.537	5.945	13.590	8.05
0.	0.45	167.08	0.227	23.923	4.891	29.041	0.00
0.	0.20	210.57	0.082	7.135	5.866	13.083	0.00
0.	0.05	260.95	0.050	1.465	7.385	8.900	0.00
CYCLE TOTALS		161.00	0.411	17.586	5.397	23.393	8.61
PERCENT OF BASELINE		100.59	17.97	73.41	100.00	73.94	

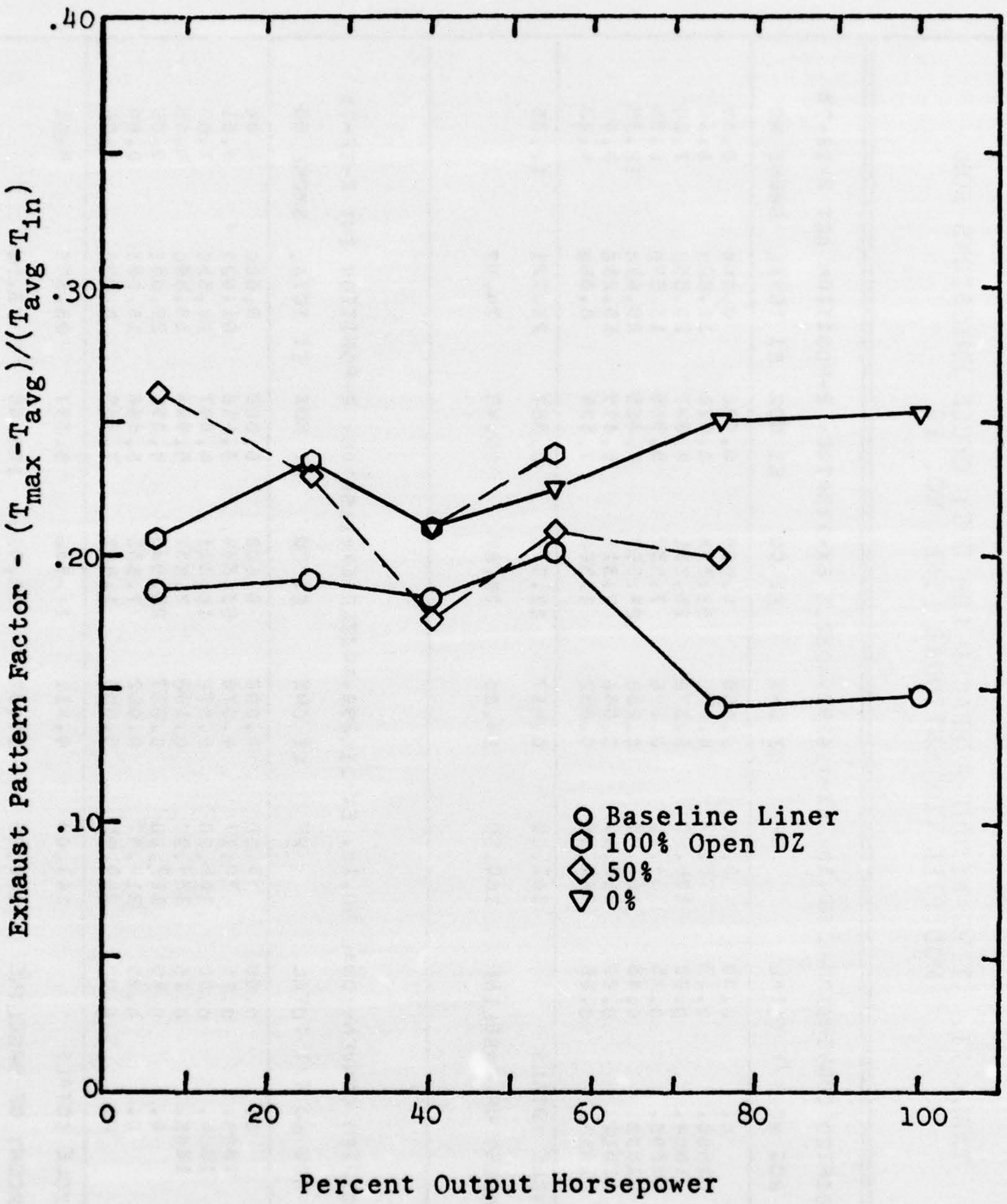


Figure 109. Modified Conventional Liner No. 10 and Baseline Liner Exhaust Pattern Factor.

LOW-EMISSION MODIFIED CONVENTIONAL COMBUSTOR (0% OPEN VG) AT 100% POWER POINT
TEST DATE = 2-12-75 READING NUMBER = 1813 INLET TEMP = 569.
ENGINE NUMBER/NAME = COMB. RIG / MODEL 250-C20B ENGINE TOT = 1490.
OUTER CASE NUMBER/NAME = 6857946-VG / VARIABLE GEOMETRY
LINER NUMBER/NAME = EX-116292 / MOD. CONV. NO. 10

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	2063.3	2000.6	1833.4	1965.8
MAXIMUM TEMPERATURE	2320.0	2237.0	1999.0	2320.0
(AVG-INLET) TEMP	1494.3	1431.6	1264.4	1396.8
(MAX-AVG) TEMP	256.7	236.4	165.6	354.2
MAX TEMP/AVG TEMP	1.1244	1.1182	1.0903	1.1802
(MAX-AVG)/(AVG-IN)	0.1718	0.1652	0.1309	0.2536
(AVG-AVG TOTAL)	97.5	34.8	-132.3	
(TIP-HUB) AVG TEMP				-229.9
(AVG TOTAL-TOT)				475.8

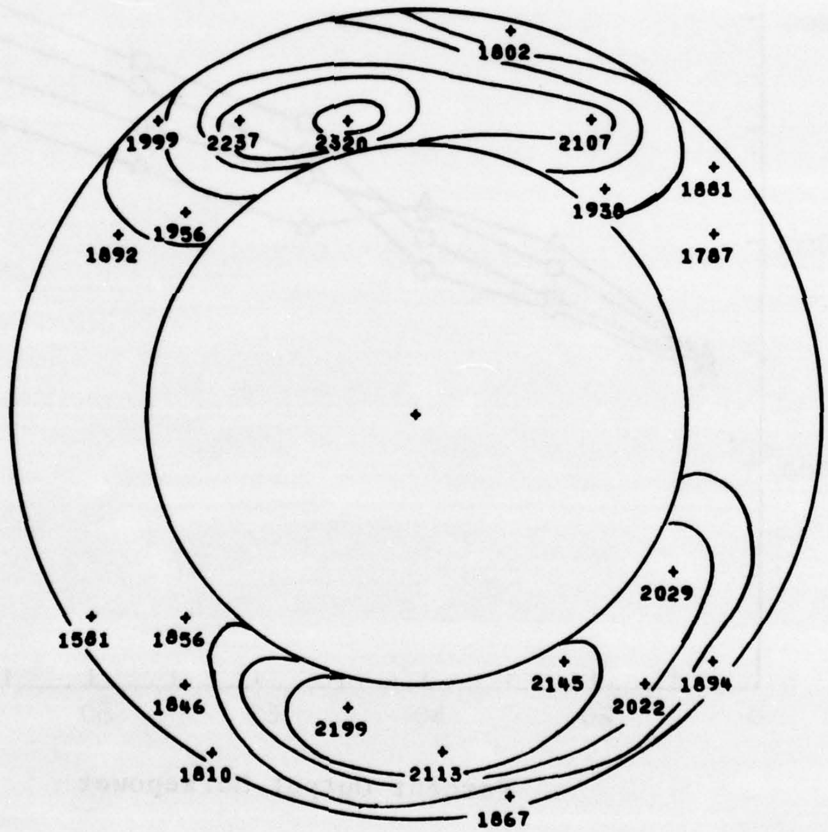


Figure 110. Modified Conventional Liner No. 10 Exhaust Temperatures at 100% Power.

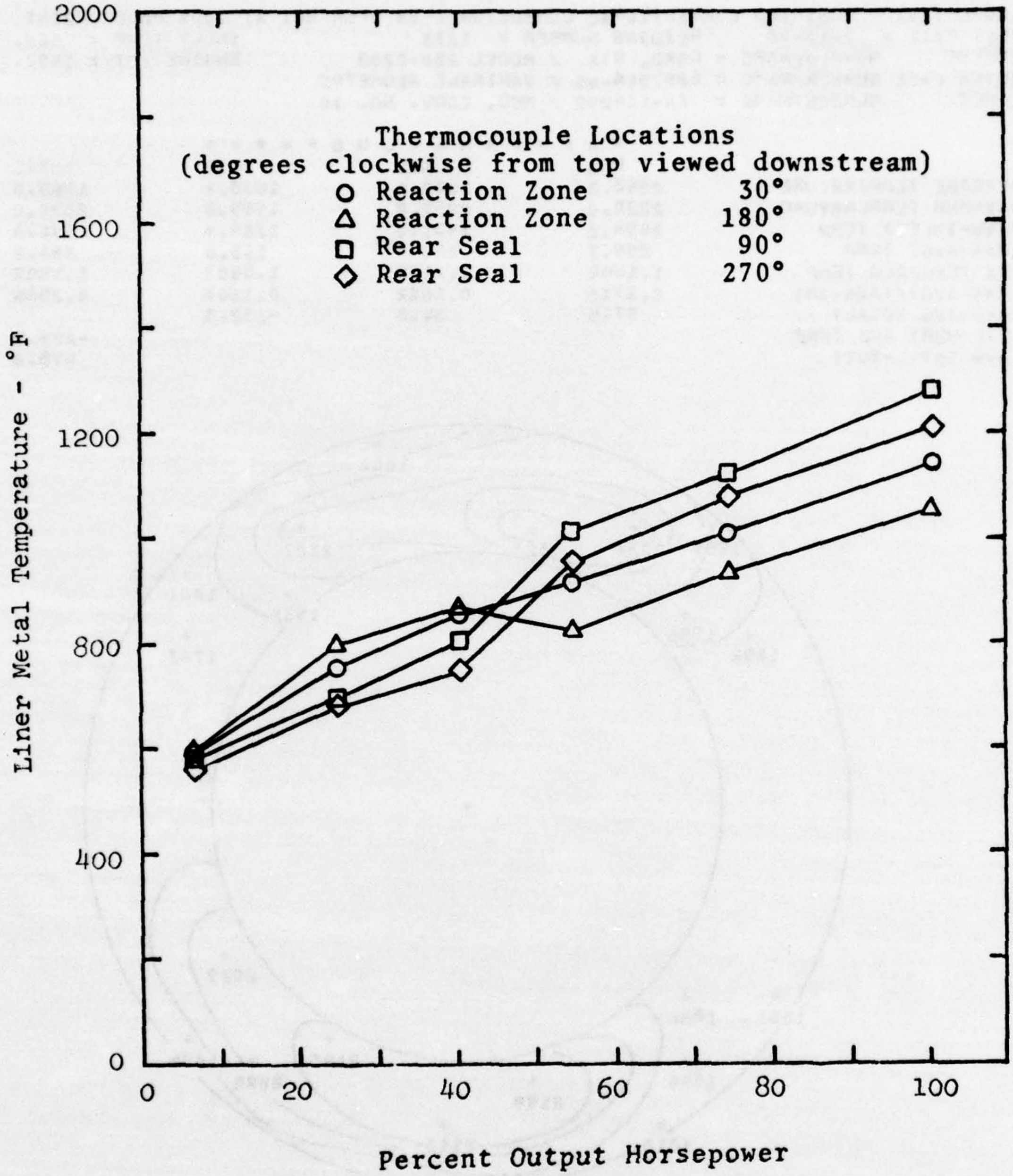


Figure 111. Modified Conventional Liner No. 10 Liner Metal Temperatures.

Summaries of the performances of all ten modified conventional liners are given in Tables 72, 73, and 74 for LOH duty cycle emissions (emission index and percent of baseline emissions), pattern, and liner metal temperature and pressure drop.

The modified conventional liner, No. 10, was coated with thermally sensitive paint and operated at 100% power conditions for twenty minutes. The interpreted paint results for this liner are presented in Figures 112 through 116.

Figures 112, 113, and 114 show the combustor after it had been tested in the high-power dilution band setting. The temperature patterns in these photographs show no temperatures above the 1400°-1706°F band and only one small area at the rear seal within this band. Figure 115 shows the dilution band rotated to the low power setting to uncover a portion of the metal covered by the dilution band in the high power setting.

A photograph of the results of the thermal paint on the inside of the modified conventional liner can be seen in Figure 116. The majority of these surfaces operated in the 968°-1400°F range, with a few areas in the next higher range of 1400°-1706°F.

The modified conventional liner should operate at very cool metal temperatures when installed in the engine, even with the convection cooling of the primary zone and the double wall construction in the dilution zone.

The modified conventional liner No. 10 underwent ambient and simulated altitude starting tests on the combustor test rig. The standard Model 250-C20B ignition system was used with the spark plug mounted in the standard position, adjacent to the fuel nozzle, through the liner dome. Ambient inlet temperature (44°-53°F) and ambient inlet pressure (14.7-15.1 psia) starting was conducted over a range of airflow rates from 0.50 to 0.69 lb/sec. Combustor pressure drops varied from 2.0 to 3.7%. Successful starts were accomplished at the conditions given in Table 75. Starts were attempted on the pilot only and on the pilot plus varying rates of airblast main fuel. No successful starts were obtained with any amount of main fuel either separately or with pilot flow.

The inlet pressure was then reduced to the 25,000 feet altitude level of 5.46 psia, where starting was again attempted with varying flow rates of pilot fuel only and pilot plus main fuel. At this condition, with an airflow rate of 0.23 lb/sec, successful starts were obtained with the pilot fuel system only at flow rates of approximately 20-25 lb/hr. One of these starts is documented in the last line of data in Table 75.

The starting tests for the modified conventional liner were conducted with DDA airblast nozzle EX-115870C having a separately controlled simplex pilot.

Modified Conventional Liner No. 11

Combustor rig testing was completed with modified conventional liner No. 10. A new combustor was fabricated for engine testing on the Model 250-C20B engine, the next portion of the program. The exhaust temperature pattern from liner No. 10 was only marginally acceptable. Therefore, the combustor fabricated for the engine testing No. 11 was changed slightly to try to produce a dilution hole pattern for high-power operation that would give a more uniform liner exhaust temperature distribution.

Modified conventional liner No. 8 had a four-dilution-hole pattern in the full closed (0% open) setting with holes ±60° to the horizontal plane. High-temperature exhaust regions were located at the sides of the turbine inlet annulus. Liner No. 10 had four of the same size holes in the same axial location but located circumferentially ±30° to the horizontal plane. High-temperature exhaust regions from this hole pattern were located at the top and bottom of the turbine inlet annulus. Therefore, the new engine combustor, modified conventional liner No. 11, was designed with the high power dilution holes ±45° to the horizontal plane. Photographs of the exterior of this liner, showing the low-power dilution setting and the high-power setting, are given in Figure 117 and an internal view is shown in Figure 118.

A liner-hole design summary for all eleven modified conventional combustors is given in Table 76. All of the modified conventional liners had the same envelope. The effective overall length was 8.800 inches and the gross overall length was 9.590 inches, which includes the .500-inch turbine inlet seal and the .290-inch fuel nozzle ferrule thickness. The internal diameter of the reaction zone was 5.25 inches and the internal diameter at the liner exit was 6.150 inches. Axial positions of the holes through the liner can be determined from the cross-sectional sketch for Liner No. 10, shown in Figure 87.

TABLE 72. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS INDEX SUMMARY FOR BASELINE AND LOW-EMISSIONS MODIFIED CONVENTIONAL COMBUSTORS FROM RIG TESTS.

Combustor Liner	Highest Cycle Power Level	Maximum Smoke Number	Emissions Index (gm/kg Fuel) (% of Baseline) C_xH_y	CO	NO_x	Total
250-C20B Baseline	100%	42.34	2.287	23.955	5.396	31.639
	75%	42.34	2.478	25.960	5.248	33.687
Modified Conventional						
1. EX-114013 (Variable)	100%	29.36	.417 18%	8.055 34%	5.998 111%	14.471 46%
2. EX-114769 (Fixed)	75%	13.12	.730 29%	9.857 38%	7.473 142%	18.061 54%
3. EX-114769A (Fixed)	75%	9.68	.507 20%	12.944 50%	5.322 101%	18.774 56%
4. EX-114770 (Variable)	100%	24.41	.356 16%	9.990 42%	5.395 100%	15.742 50%
5. EX-115257 (Variable)	100%	44.58	2.452 107%	21.709 91%	5.383 100%	29.544 93%
6. EX-115860 (Variable)	100%	13.91	.555 24%	13.733 57%	5.323 99%	19.613 62%
7. EX-115887 (Variable)	100%	8.75	.183 8%	11.235 47%	5.374 100%	16.793 53%
8. EX-115895 (Variable)	100%	13.61	.546 24%	13.500 56%	5.389 100%	19.436 61%
9. EX-116289 (Variable)	100%	5.91	.369 16%	13.671 57%	5.646 105%	19.688 62%
10. EX-116292 (Variable)	100%	11.45	.411 18%	17.586 73%	5.397 100%	23.393 74%

TABLE 73. EXHAUST TEMPERATURE PROFILES FROM BASELINE AND LOW-EMISSIONS MODIFIED CONVENTIONAL COMBUSTORS USING TEST RIG DATA.

Combustor Liner	Pattern Factor, $(T_m-T_a)/(T_a-T_{in})$		T_m/T_a	
	75% Power	100% Power	75% Power	100% Power
Acceptable Maximum	--	.250	--	1.180
Baseline 250-C20B	.143	.148	1.101	1.106
Modified Conventional				
1. EX-114013	.140	.267	1.096	1.184
2. EX-114769	.268	--	1.190	--
3. EX-114769A	.212	.274	1.149	1.192
4. EX-114770	.152	--	1.108	--
5. EX-115257	.196	.225	1.139	1.159
6. EX-115860	.271	.234	1.189	1.165
7. EX-115887	.307	.229	1.212	1.161
8. EX-115895	.261	.266	1.179	1.184
9. EX-116289	.300	.175	1.213	1.126
10. EX-116292	.250	.253	1.176	1.180

TABLE 74. MAXIMUM MEASURED METAL TEMPERATURES AND COMBUSTION SYSTEM PRESSURE DROPS FROM BASELINE AND LOW-EMISSIONS MODIFIED CONVENTIONAL LINERS USING TEST RIG DATA

Combustion Liner	Maximum Metal Temperature, °F		Pressure Drop, %ΔP/P	
	75% Power	100% Power	75% Power	100% Power
Acceptable Maximum	--	1700.	--	5.00
Baseline 250-C20B	1315.	1505.	3.72	3.81
Modified Conventional				
1. EX-114013	1102.	1296.	4.89	4.40
2. EX-114769	931.	--	4.83	--
3. EX-114769A	910.	1015.	5.08	5.15
4. EX-114770	1146.	--	6.01	--
5. EX-115257	1291.	1429.	3.43	3.54
6. EX-115860	1085.	1279.	4.17	4.04
7. EX-115887	1190.	1336.	5.66	4.62
8. EX-115895	1262.	1419.	5.50	5.39
9. EX-116289	1267.	1270.	5.87	4.82
10. EX-116292	1128.	1283.	5.30	5.00

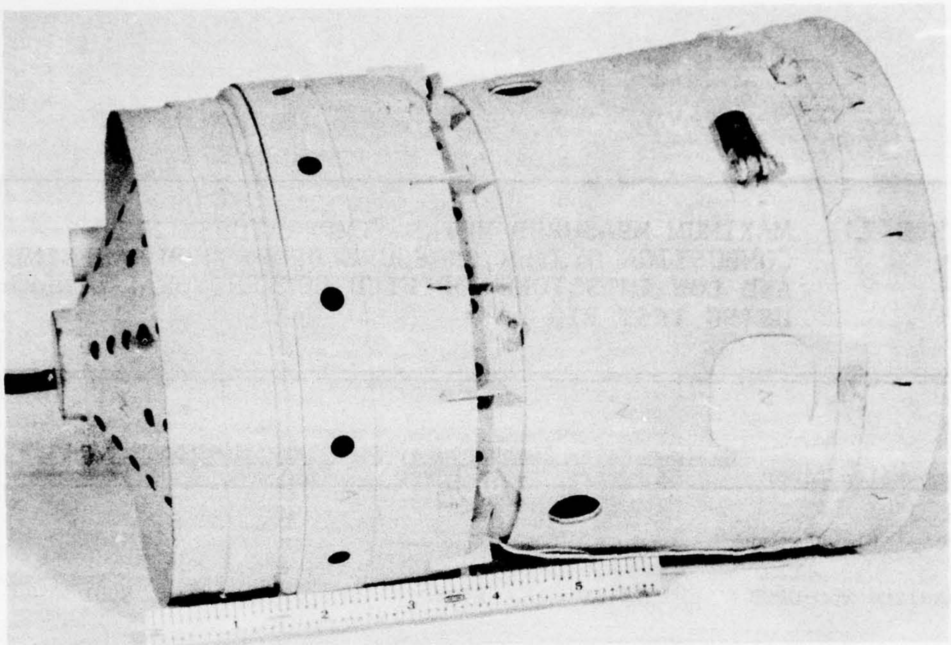


Figure 112. Modified Conventional Liner No. 10 Metal Temperature Pattern at 100% Power, External 300°-60° Rotation—High Power Setting.

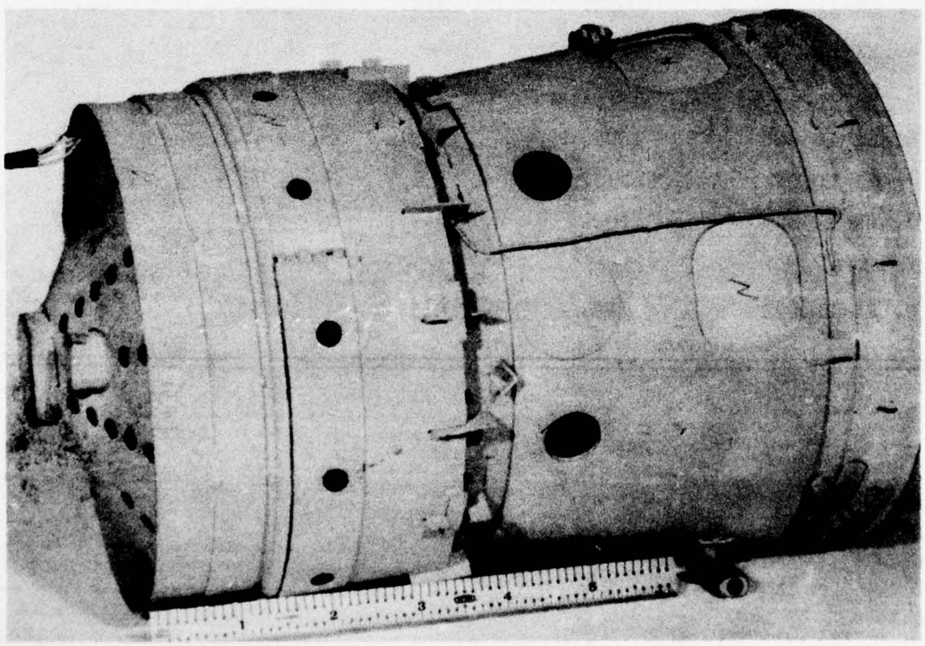


Figure 113. Modified Conventional Liner No. 10 Metal Temperature Pattern at 100% Power, External 60°-180° Rotation—High Power Setting.

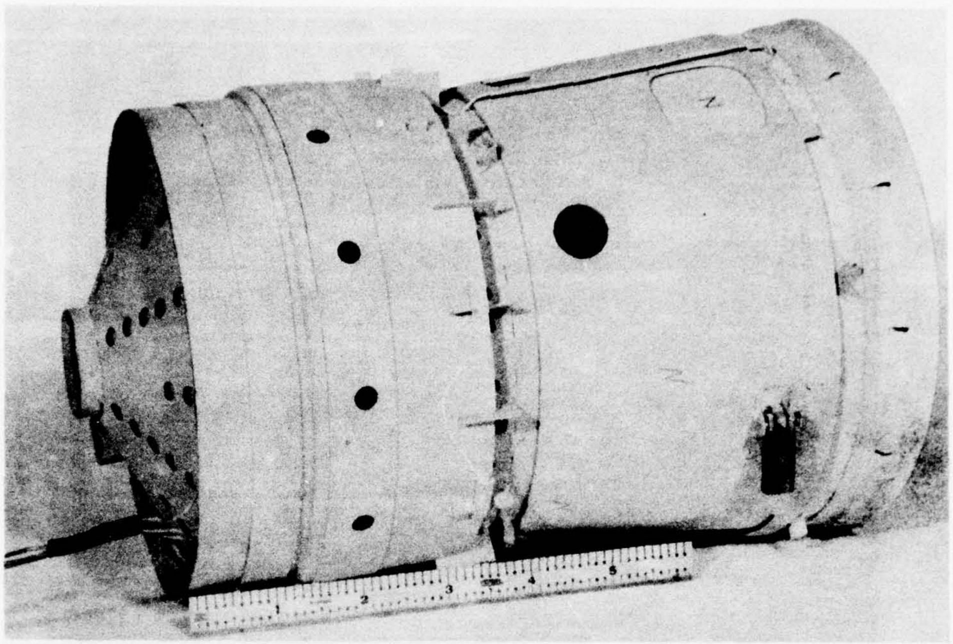


Figure 114. Modified Conventional Liner No. 10 Metal Temperature Pattern at 100% Power External 90°-210° Rotation—High Power Setting.

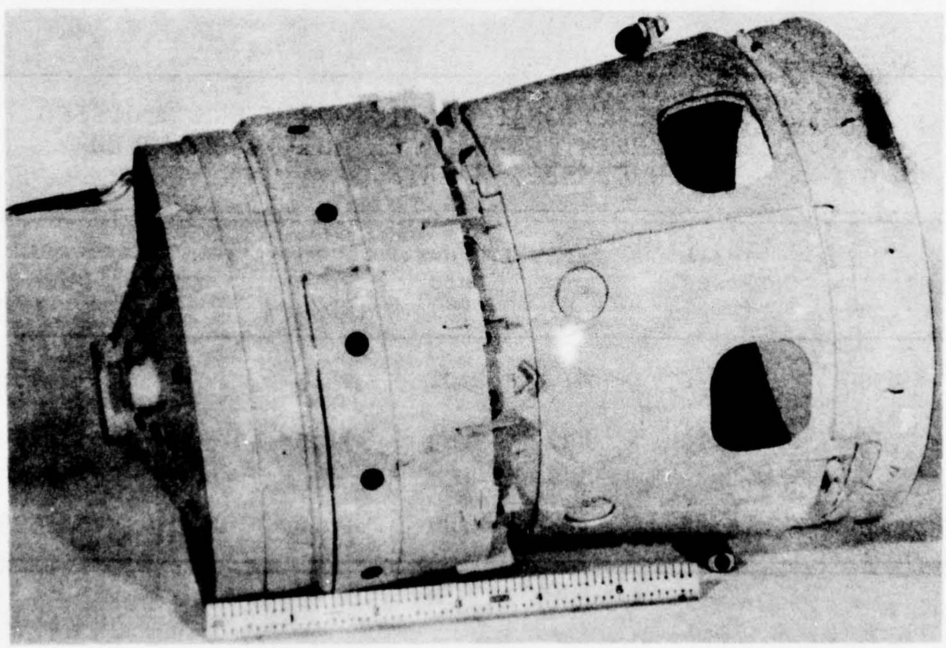


Figure 115. Modified Conventional Liner No. 10 Metal Temperature Pattern at 100% Power External 0°-180° Rotation—Low Power Setting.

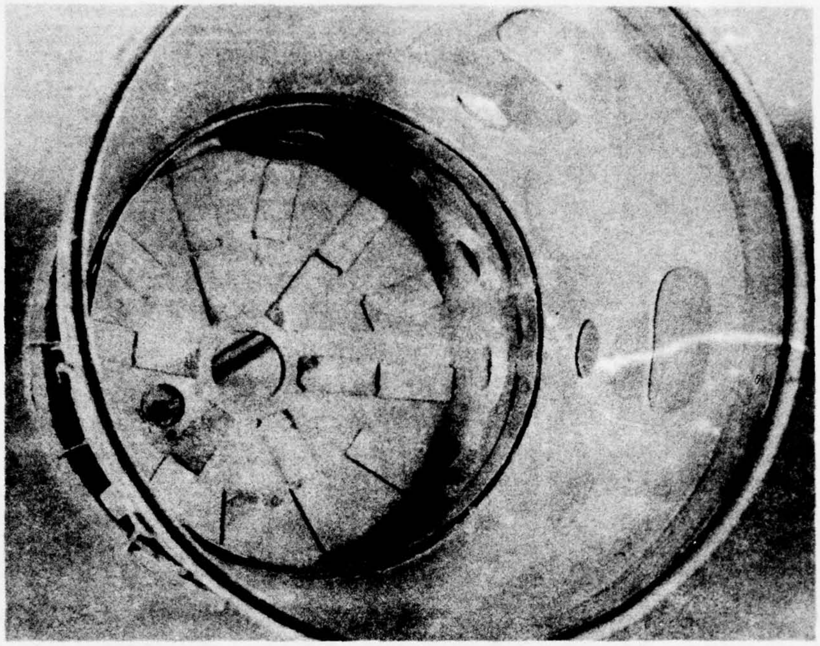


Figure 116. Modified Conventional Liner No. 10 Metal Temperature Pattern at 100% Power, Internal.

TABLE 75. OPERATIONAL CONDITIONS WHERE MODIFIED CONVENTIONAL LINER NO. 10 ACHIEVED SUCCESSFUL STARTS.

Airflow (lb/sec)	Inlet Press. (psia)	Inlet Temp. (°F)	Press. Drop (%)	Fuel Flow Pilot (lb/hr)	Fuel Flow Main (lb/hr)	Outlet Temp. (°F)
.500	14.72	47.	2.01	25.3	-	468.
.691	15.10	43.	3.69	34.5	-	555.
.229	5.38	40.	3.25	20.6	-	503.

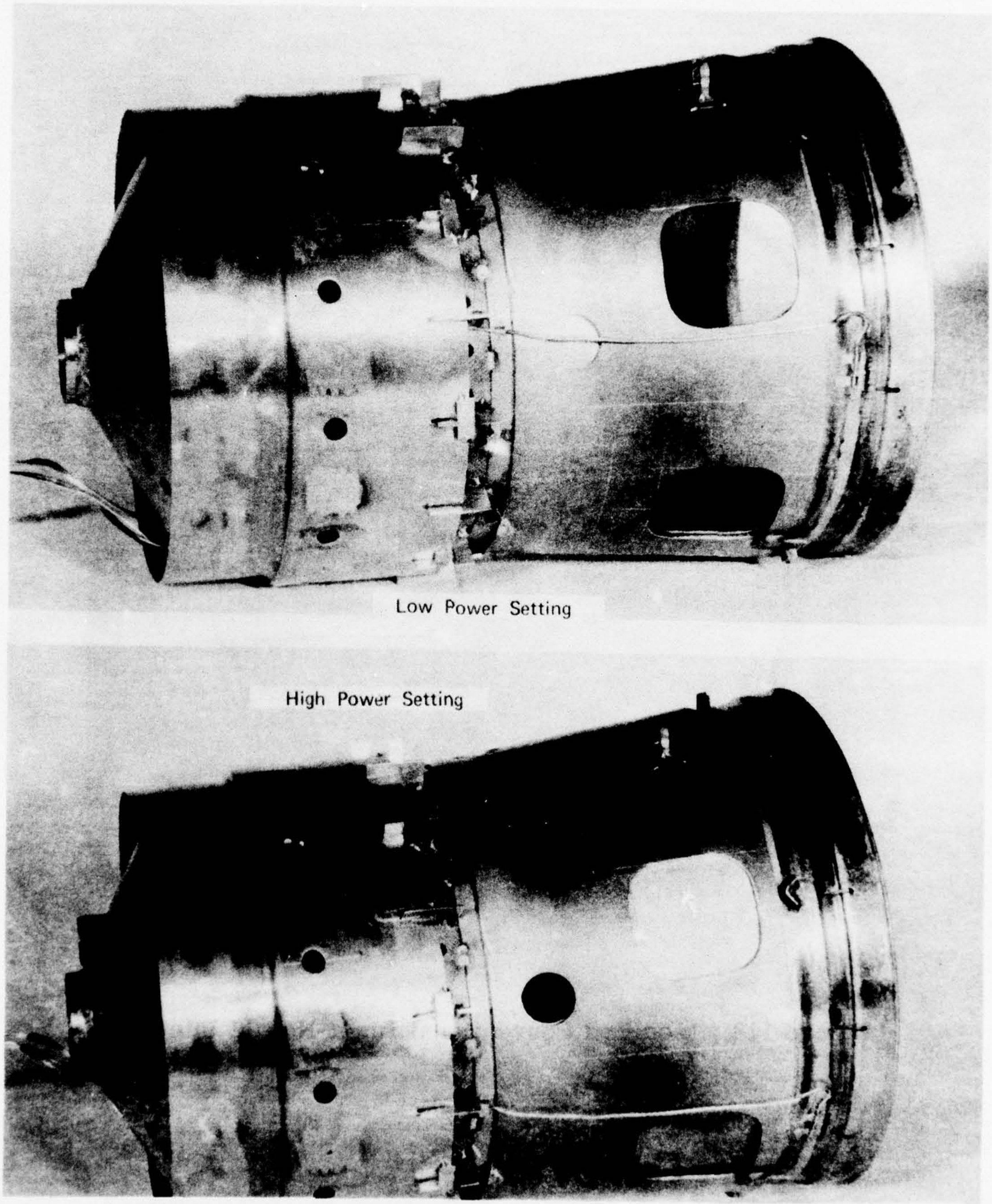


Figure 117. Modified Conventional Liner No. 11 External Views.

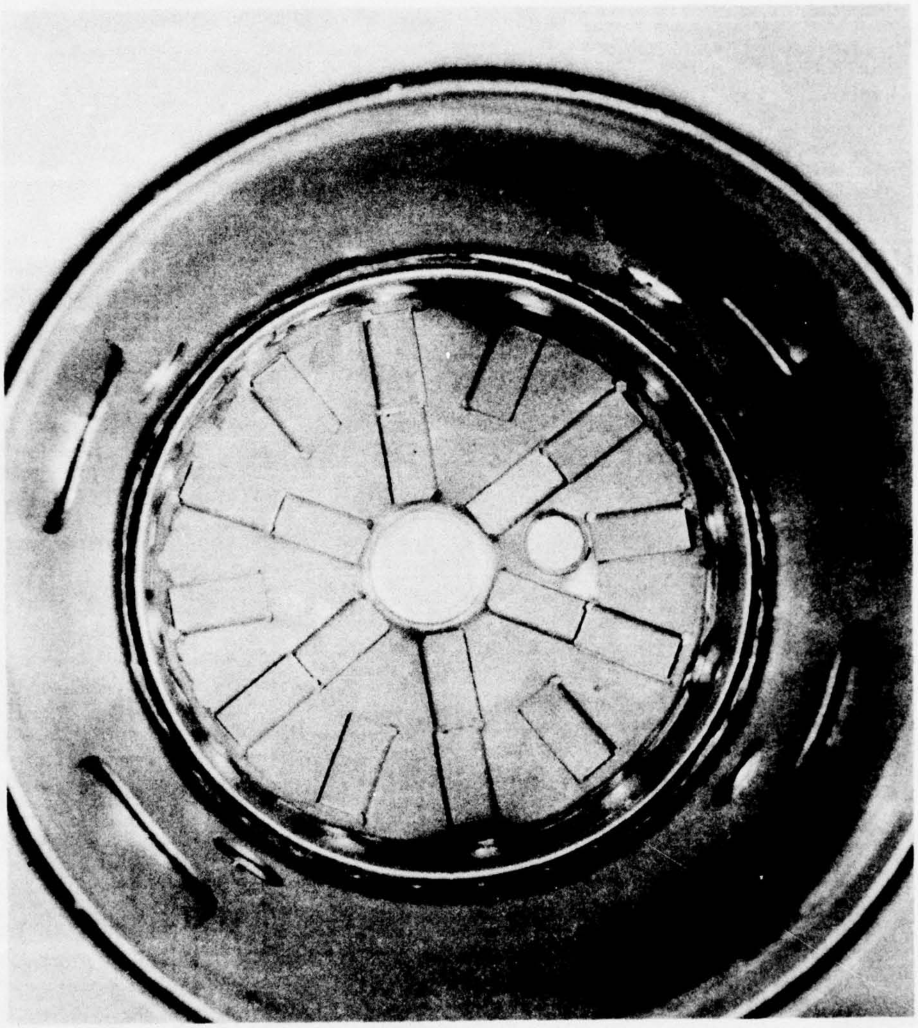


Figure 118. Modified Conventional Liner No. 11 Internal View.

TABLE 76. MODIFIED CONVENTIONAL LINER HOLE DESIGN SUMMARY.

Design Number	1	2	3	4	5	6	7	8	9	10	11
Hole Description (No.) Dia											
Dome	(54).203	(54).203	(54).203	(54).203	(54).203	(54).203	(54).203	(54).203	(54).203	(54).203	(54).203
Primary Zone											
Shroud	-	-	-	-	(12).500	-	-	-	-	(12).250	(12).250
Liner											
Penetration	(12).500	(12).561	(12).561	(12).561	(12).750	(12).652	(12).500	(12).500	(12).562	(12).562	(12).562
Anti-Flame	-	-	-	-	-	(12).125	(12).125	(12).125	(12).125	(12).125	-
Film Cooling	(48).172	(48).172	(48).172	(48).172	(48).172	(48).172	(48).172	(48).172	(32).172	(32).172	(32).172
Dilution Zone											
Upstream											
No.	4	-	-	-	-	-	-	4	2	4	4
Dia	1.22x1.41*	-	-	-	-	-	-	.625	.625	.625	.625
± Angle to Horizontal	30°	-	-	-	-	-	-	60°	0°	30°	45°
Downstream											
No.	-	4	4	4	4	4	4	4	4	4	4
Dimensions*	-	∅.938	∅.812	1.22x1.40	1.22x1.40	1.22x1.40	1.22x1.40	1.22x1.40	1.22x1.40	1.22x1.40	1.22x1.50
± Angle to Horizontal	-	30°	30°	30°	30°	30°	30°	30°	30°	30°	30°

* Rectangular holes have 0.41 inch radius corners

ENGINE TESTING

Following the development of acceptable configurations of the prechamber and modified conventional combustors, new combustor hardware was fabricated for the testing of these combustors on a Model 250-C20B turboshaft engine. The production combustor system was tested on a Model 250-C20B engine to document baseline exhaust emissions, performance, and combustor exit temperature profile, both before and after low-emission combustor engine testing.

Each low-emission combustor was engine tested for combustor exit temperature profile, and the dilution holes were adjusted as necessary until an acceptable profile was achieved. Each combustor was then tested for exhaust emissions and performance. The prechamber combustor was further engine tested over a forty-hour cyclic durability profile to assess life potential, and a series of exhaust emissions measurements were taken when the engine was operated on fuels other than JP-4 reference: JP-4 regular, JP-5 regular, and a research quantity of oil shale fuel refined toward a JP-5/Jet-A specification.

After the testing was completed, analyses were performed to assess combustor rig to engine correlation and the effects on engine performance of the low-emission combustors relative to the baseline engine performance.

The work performed in each of these areas is discussed in the following sections.

EXPERIMENTAL SYSTEM

Two dynamometer test facilities were used to conduct the various tests on the Model 250-C20B engine used in this program. These two test stands, TC140 and TC142, are located in DDA Plant No. 5, Indianapolis, Indiana. Both stands shared the same control room and were operated by the same crews, but each stand incorporated different equipment to efficiently conduct different types of engine tests. Test Cell 142 was served by equipment to condition the air to allow the inlet temperature and pressure to be accurately controlled for performance evaluation under consistent test conditions. Engines are connected to high-speed, eddy-current brakes, each having a maximum load absorption of 1000 hp, or 746 kw. This test stand was used to test engine performance, to document combustor exhaust temperatures and to measure engine exhaust emissions.

Test Cell 140 was not served by conditioned air and thus could only be utilized when ambient inlet conditions were permissible. Because of this lack of inlet conditioning and because this test stand incorporated an Automatically Controlled Endurance System, Version VI (ACES-VI) which permitted unmanned, preprogrammed endurance testing, Test Cell 140 was used for the durability engine testing of the prechamber combustor. This control system, along with the equipment to simulate environmental vibration parameters, is shown in Figure 119.

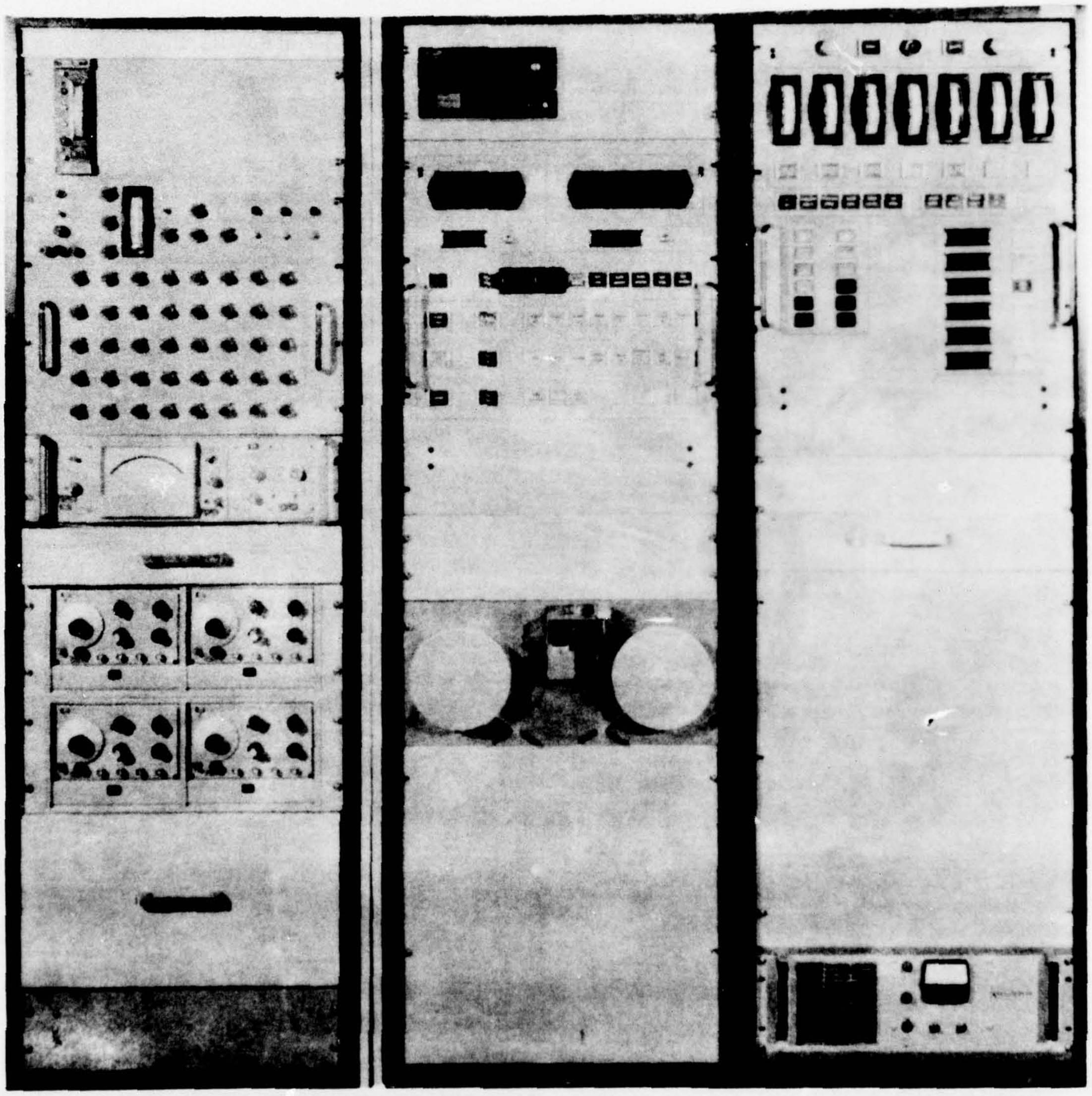


Figure 119. Automatically Controlled Endurance System, Version VI, (ACES VI) Equipment Used During Prechamber Durability Engine Test.

Combustion exit temperatures were recorded with the thermocouple instrumentation ring shown in Figure 120. This instrumentation ring contains forty-eight, closed-tip chromel-alumel thermocouples equally spaced around the exhaust annulus of the liner. Sixteen thermocouples were set at each of three depths across the annulus, corresponding to the centers of three equal-area annuli. Also, at the top and bottom of the annulus were total pressure probes to measure combustor outlet pressure. The circular spaces on each side of the instrumentation ring are clearances for the two engine air tubes which carry the compressor discharge air to the combustor.

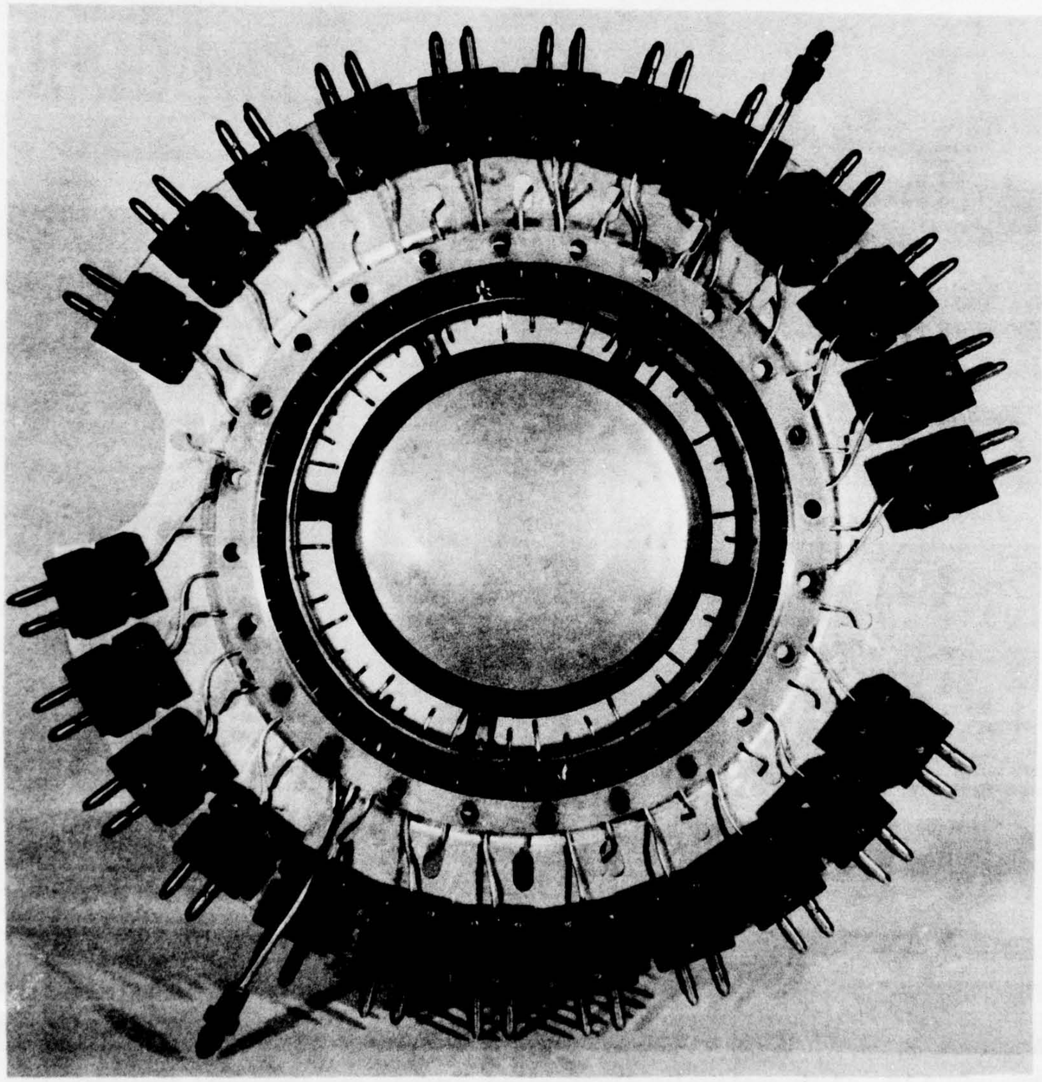


Figure 120. Engine Instrumentation Ring Used to Measure Combustor Exhaust Performance.

Engine exhaust emissions were sampled at both exhaust diffuser exits with a cruciform averaging probe conforming to Section 87.63 of the EPA Emissions Standards and Test Procedures of Aircraft. Gas samples from the exhaust probes were connected to a common sample line, maintained at 150°C, which transported the gas sample to the portable emissions analysis equipment. The emissions equipment shown in Figure 121 measures carbon monoxide (CO), total oxides of nitrogen (NO_x), total unburned hydrocarbons as methane (CH_x), carbon dioxide (CO_2), oxygen (O_2), and smoke. The particular emissions instruments are identified in Table 77. Concentrations of all exhaust constituents from the engine were measured and reported on a wet basis. A schematic diagram of the gas sample instrumentation system arrangement is shown in Figure 122.

TABLE 77. EMISSIONS INSTRUMENTS USED IN ENGINE TESTING

Emission	Method	Instrument	Ranges	Accuracy
Oxides of nitrogen (NO_x)	Chemiluminescence	Thermo electron (Model 10A with converter)	0-2.5, 0-10, 0-250 and 0-1000 ppm	± 1% F.S.
Carbon monoxide + Water vapor	Nondispersive infrared	Beckman (Model 865)	(C) 0-100, 0-500 0-2500 ppm (tho) 0-5%	± 2%
Carbon dioxide (CO_2)	Nondispersive infrared	Beckman (Model 864)	0-5%	± 1%
Unburned hydrocarbons (HC_x)	Flame ionization detector	Beckman (Model 402)	0-10, 0-50, 0-100, 0-1000 ppm	± 1%

BASELINE COMBUSTOR

Installation of the Model 250-C20B engine was accomplished in Test Cell 142 at DDA Plant 5. The serial number of this engine was S/N 821233. A gas flow diagram of a Model 250-C20B engine is presented in Figure 123 and identifies the measurement stations used. Combustor inlet conditions are identified as station 3 (compressor discharge), although one thermocouple and one pressure probe were installed through the dome of the combustor outer case. During engine performance and emissions measurements, there was no instrumentation at the combustor exit or station 4 (gas producer turbine inlet). For combustor exit temperature and pressure measurements, the instrumentation ring, shown in Figure 120,

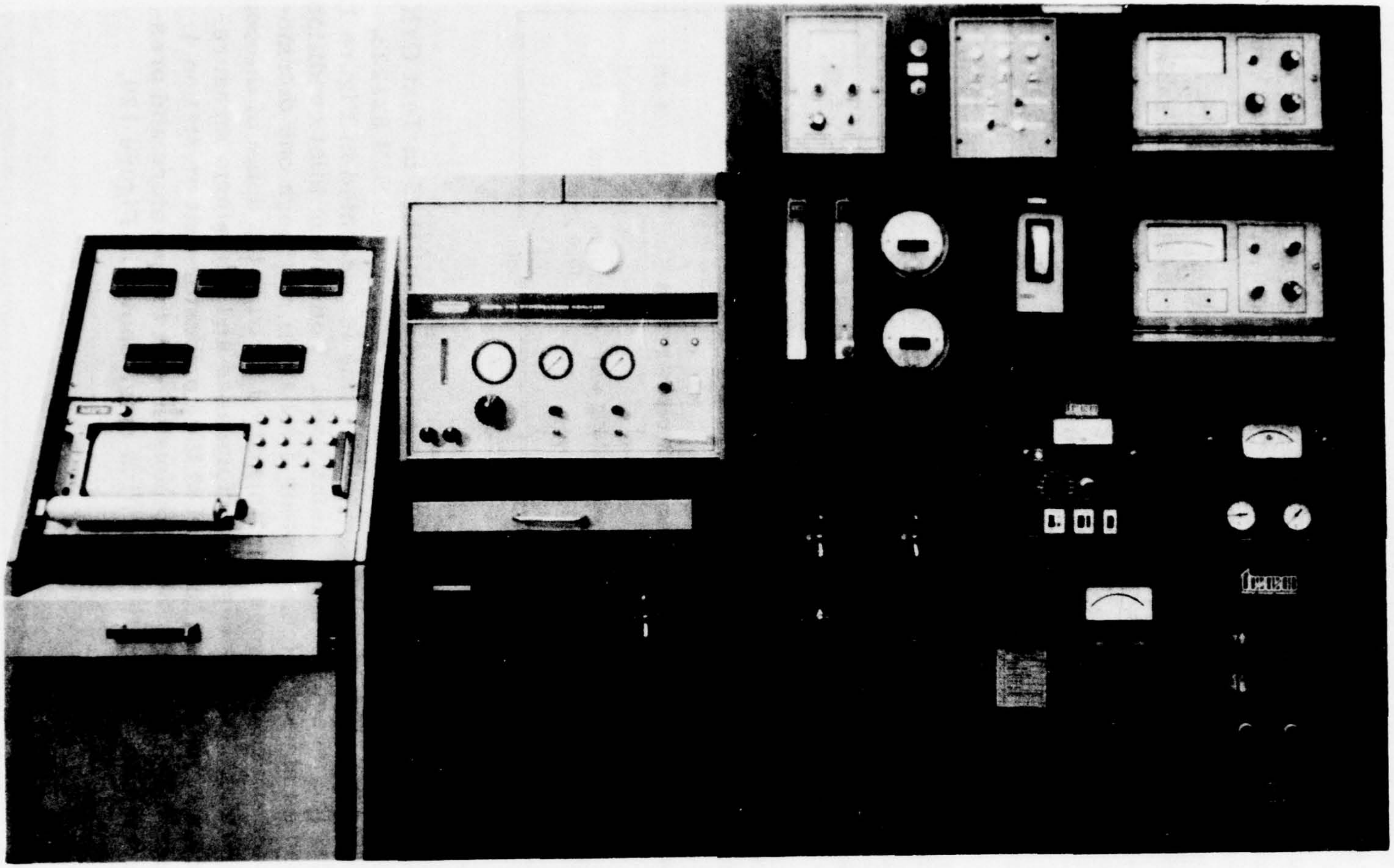


Figure 121. Portable Exhaust Emissions Instrument Bench Used to Measure Engine Emissions.

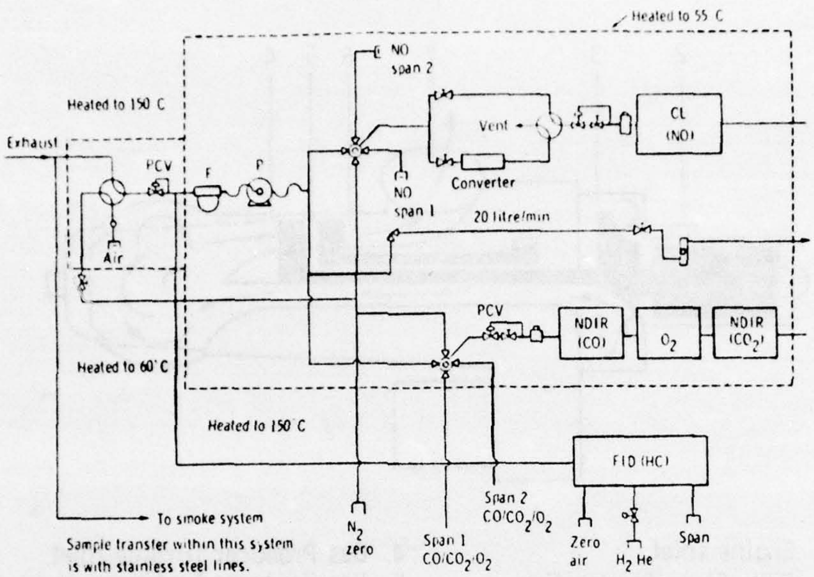


Figure 122. Emissions Instrument System Schematic.

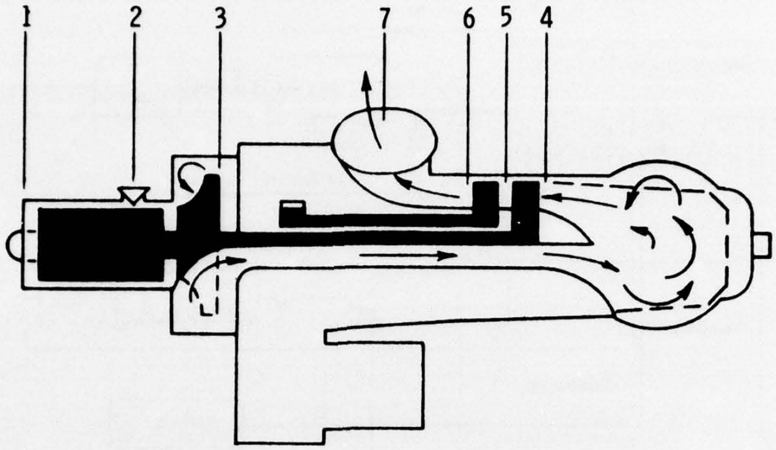
and previously described was installed. Engine power was set by monitoring four equally spaced station 5 thermocouples between the two turbines. These were permanently mounted thermocouples which were installed in every engine and were used by the fuel control system.

Performance

Engine performance measurements are shown in Table 78 as corrected to standard day. Due to a malfunction with the combustor inlet temperature thermocouple, no T3 temperatures were recorded. However, the remaining performance parameters were satisfactory.

The performance of the engine was satisfactory and representative of the Model 250-C20B engine. The engine was operated at the LOH duty cycle operating conditions to document the engine's operation prior to any further baseline or low emissions testing.

Eight data points were taken at power levels corresponding to ground and operational idle, 25, 40, 55, 75, and 100% shaft output horsepower. The



1. Engine Inlet
2. Fifth-Stage Acceleration Bleed Port
3. Compressor Discharge
4. Gas Producer Turbine Inlet
5. Gas Producer Turbine Outlet
6. Power Turbine Discharge
7. Engine Outlet

Figure 123. Model 250-C20B Engine Gas Flow Diagram.

75% power point was measured twice, once at the beginning of the test and once at the end. Engine operating conditions corrected to standard day are recorded in Table 79 and show that the desired power levels were adequately achieved within a few percent. The individual parameters duplicated well with the performance calibration. To set the engine operating point, the four gas producer turbine-outlet temperature thermocouples are averaged, and this indicated temperature can be repeated within a few degrees to repeat any operating condition.

Exhaust Temperature Profiles

The gas producer turbine-inlet instrumentation ring was installed on the baseline engine to document the baseline combustor exhaust-temperature pattern. Due to the blockage of this instrumentation (48 thermocouple probes and 2 pressure probes) takeoff horsepower could not be achieved, but combustor conditions at takeoff were repeated. Engine operating conditions for the four data points measured are shown in Table 80. In this test, ground idle, 40, 75, and 100% power points were recorded. The individual thermocouple temperatures (uncorrected) are recorded in Figures 124 through 127. For each power condition, the T_{max}/T_{avg} temperature ratio was approximately 1.11, and the pattern factors ranged

TABLE 78. MODEL 250-C20B ENGINE BASELINE PERFORMANCE INITIAL CALIBRATION (CORRECTED TO STANDARD DAY)

Engine Power		Compressor Speed, N_1	Combustor Inlet		Total Engine			Gasifier Turbine Outlet Temp, T_5
			Temp, T_3	Press., P_3	Airflow	Fuel Flow		
(%)	(HP)	(rpm)	(°R)	(lb/in^2 abs)	(lb/sec)	(lb/hr)	f/a	(°R)
58	242	47,000	-*	81.6	3.07	177.0	.0160	1660
65	274	47,928	-	87.1	3.17	191.0	.0168	1695
73	307	48,815	-	90.7	3.27	202.2	.0172	1740
82	345	49,912	-	94.9	3.37	217.3	.0179	1794
101	423	52,359	-	103.6	3.56	256.5	.0201	1926

* Instrumentation in error, no temperatures recorded.

TABLE 79. MODEL 250-C20B ENGINE BASELINE PERFORMANCE DURING STEADY-STATE EXHAUST EMISSION TEST (CORRECTED DATA)

Mode	Desired Power (%)	Actual Power (%)	Actual Power (HP)	Reading Number	Gasifier Speed, N_1 (rpm)	Air Flow Wa (lb/sec)	Fuel Flow W_f (lb/hr)	f/a	Gasifier Turbine Outlet Temp, T5 (°R)
Ground Idle	1	-3	-12	196	31,004	1.74	60.8	.0097	1277
Operational Idle	6	6	26	197	36,081	2.22	80.9	.0101	1350
-	25	27	118	198	42,300	2.70	122.9	.0126	1489
Approach	40	42	184	195	44,941	2.93	150.1	.0142	1572
Cruise	55	58	252	199	47,319	3.10	178.4	.0160	1660
Climb/Hover	75	79	341	194	49,584	3.36	217.7	.0180	1787
		78	339	201	49,750	3.35	217.7	.0181	1778
Take-off	100	100	433	200	52,660	3.57	264.4	.0206	1944

TABLE 80. MODEL 250-C20B ENGINE BASELINE PERFORMANCE DURING STEADY-STATE EXHAUST TEMPERATURE MEASUREMENTS (CORRECTED DATA)

Mode	Desired Power (%)	Actual Power (%)	Actual Power (HP)	Reading Number	Gasifier Speed, N_1 (rpm)	Air Flow Wa (lb/sec)	Fuel Flow Wf (lb/hr)	f/a	Gasifier Turb. Outlet Temp, T_5 (°R)
Ground Idle	1	-3	-13	202	31031	1.73	61.7	.0099	1284
Approach	40	43	185	203	44915	2.91	150.6	.0144	1576
Climb/Hover	75	78	339	204	49641	3.33	210.3	.0175	1778
Take-off	100	96	414	205	51960	3.54	251.4	.0197	1905

BASELINE COMBUSTOR SYSTEM OPERATING AT 1% POWER TURBINE TEMPERATURE
TEST DATE = 10-11-74 READING NUMBER = 202 INLET TEMP = 243.
ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 885.
OUTER CASE NUMBER/NAME = EX-115283 / INSTRUMENTED PROD.
LINER NUMBER/NAME = 6871486 / PRODUCTION BASELINE

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1142.7	1166.9	1165.3	1158.6
MAXIMUM TEMPERATURE	1235.0	1280.0	1295.0	1295.0
(AVG-INLET) TEMP	899.7	923.9	922.3	915.6
(MAX-AVG) TEMP	92.3	113.1	129.7	136.4
MAX TEMP/AVG TEMP	1.0808	1.0969	1.1113	1.1177
(MAX-AVG)/(AVG-IN)	0.1026	0.1224	0.1406	0.1489
(AVG-AVG TOTAL)	-16.0	8.3	6.7	
(TIP-HUB) AVG TEMP				22.6
(AVG TOTAL-TOT)				273.6

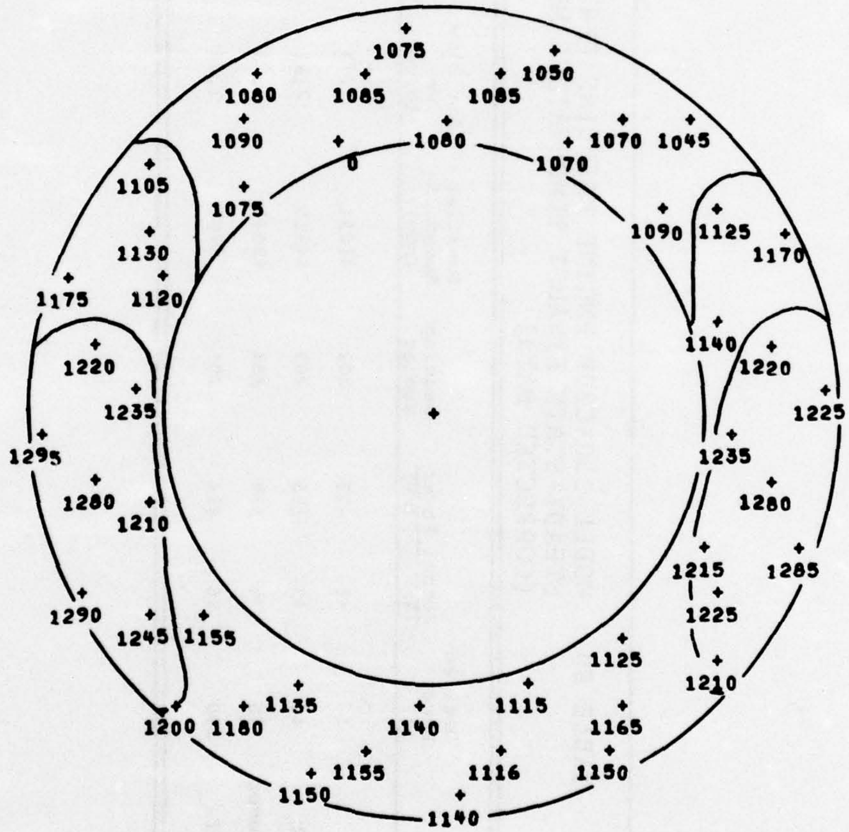


Figure 124. Baseline Liner Exhaust Temperatures on Engine at Ground Idle.

BASELINE COMBUSTOR SYSTEM OPERATING AT 40% POWER TURBINE TEMPERATURE
TEST DATE = 10-11-74 READING NUMBER = 203 INLET TEMP = 447.
ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 1120.
OUTER CASE NUMBER/NAME = EX-115283 / INSTRUMENTED PROD.
LINER NUMBER/NAME = 6871486 / PRODUCTION BASELINE

	ANNULUS HUB	ANNULUS MID	ANNULUS TIP	TOTAL
AVERAGE TEMPERATURE	1528.7	1562.8	1568.4	1553.8
MAXIMUM TEMPERATURE	1685.0	1665.0	1725.0	1725.0
(AVG-INLET) TEMP	1081.7	1115.8	1121.4	1106.8
(MAX-AVG) TEMP	156.3	102.2	156.6	171.2
MAX TEMP/AVG TEMP	1.1023	1.0654	1.0998	1.1102
(MAX-AVG)/(AVG-IN)	0.1445	0.0916	0.1396	0.1546
(AVG-AVG TOTAL)	-25.2	9.0	14.6	
(TIP-HUB) AVG TEMP				39.8
(AVG TOTAL-TOT)				433.8

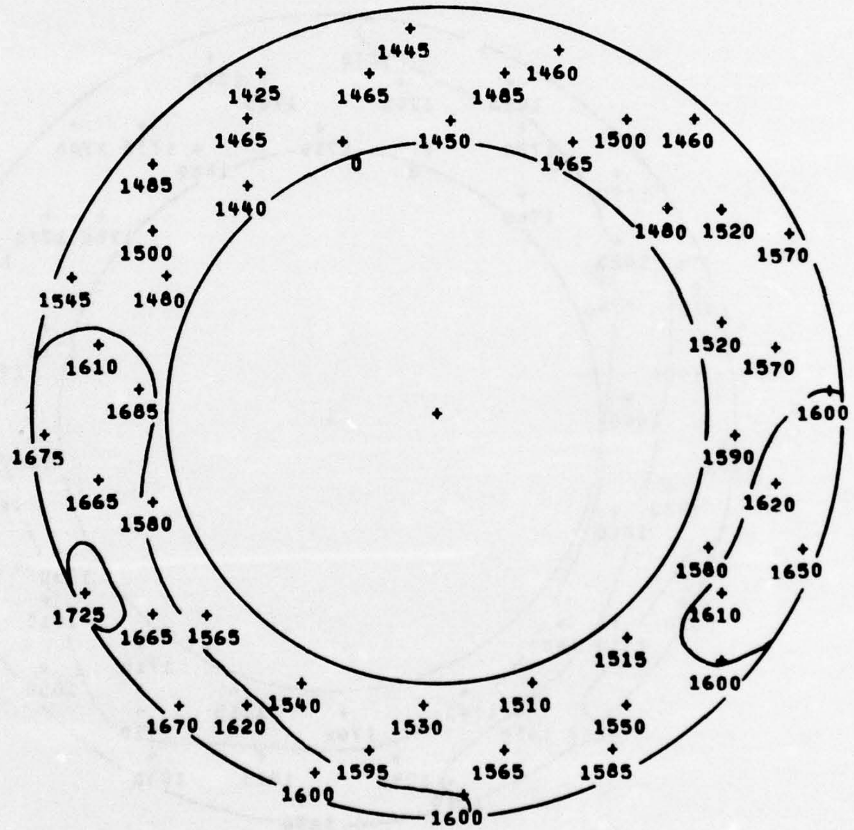


Figure 125. Baseline Liner Exhaust Temperatures on Engine at 40% Power.

BASELINE COMBUSTOR SYSTEM OPERATING AT 75% POWER TURBINE TEMPERATURE
TEST DATE = 10-11-74 READING NUMBER = 204 INLET TEMP = 529.
ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 1330.
OUTER CASE NUMBER/NAME = EX-115283 / INSTRUMENTED PROD.
LINER NUMBER/NAME = 6871486 / PRODUCTION BASELINE

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1749.3	1823.7	1865.6	1814.3
MAXIMUM TEMPERATURE	1880.0	1930.0	2010.0	2010.0
(AVG-INLET) TEMP	1220.3	1294.7	1336.6	1285.3
(MAX-AVG) TEMP	130.7	106.2	144.4	195.7
MAX TEMP/AVG TEMP	1.0747	1.0583	1.0774	1.1079
(MAX-AVG)/(AVG-IN)	0.1071	0.0821	0.1080	0.1523
(AVG-AVG TOTAL)	-64.9	9.5	51.4	
(TIP-HUB) AVG TEMP				116.3
(AVG TOTAL-TOT)				484.3

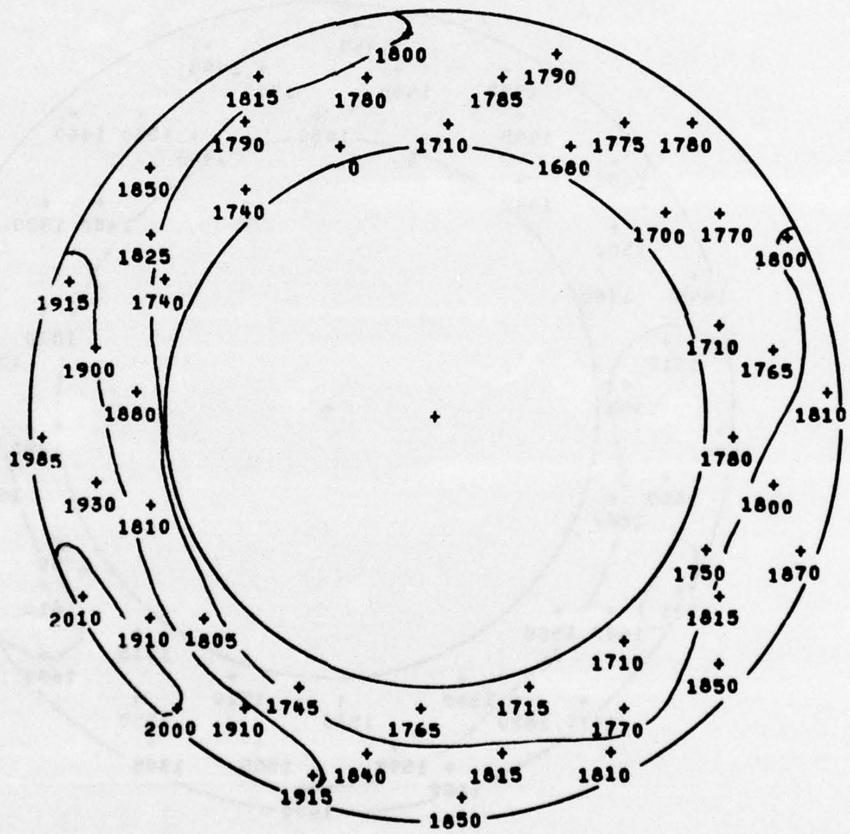


Figure 126. Baseline Liner Exhaust Temperatures on Engine at 75% Power.

BASELINE COMBUSTOR SYSTEM OPERATING AT 100% POWER TURBINE TEMPERATURE
TEST DATE = 10-11-74 READING NUMBER = 205 INLET TEMP = 564.
ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 1455.
OUTER CASE NUMBER/NAME = EX-115283 / INSTRUMENTED PROD.
LINER NUMBER/NAME = 6871486 / PRODUCTION BASELINE

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1889.3	1976.2	2018.7	1963.0
MAXIMUM TEMPERATURE	2010.0	2085.0	2150.0	2150.0
(AVG-INLET) TEMP	1325.3	1412.2	1454.7	1399.0
(MAX-AVG) TEMP	120.7	108.7	131.2	187.0
MAX TEMP/AVG TEMP	1.0639	1.0550	1.0650	1.0953
(MAX-AVG)/(AVG-IN)	0.0910	0.0770	0.0902	0.1337
(AVG-AVG TOTAL)	-73.6	13.3	55.8	
(TIP-HUB) AVG TEMP				129.4
(AVG TOTAL-TOT)				508.0

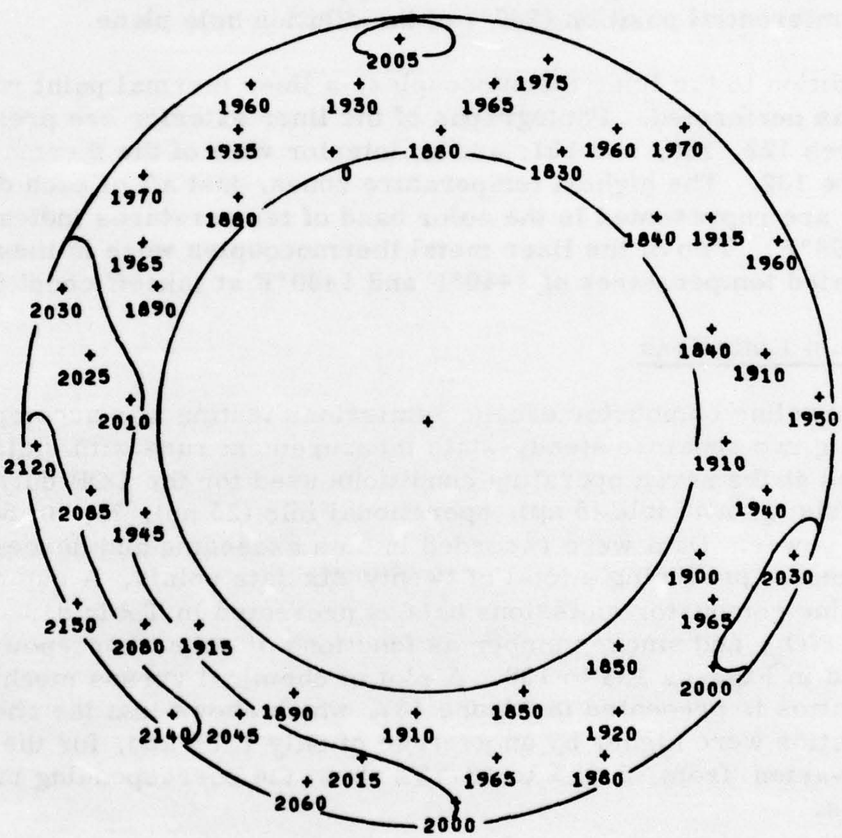


Figure 127. Baseline Liner Exhaust Temperatures on Engine at 100% Power.

from .15 to .13 across the power range. The temperature pattern was roughly symmetric about a line passing through 2 and 8 o'clock positions looking downstream. The temperatures at the 2 o'clock positions were the coldest, with temperatures increasing around the annulus to the hottest temperatures at the 8 o'clock position. Comparison of engine and combustor rig exhaust pattern parameters at 100% power were 1.095 for the engine and 1.106 for the rig for T_{max}/T_{avg}, and 0.134 engine and 0.148 for the rig for the pattern factor.

Liner metal temperatures were monitored for all of the data points recorded. These temperatures are plotted in Figure 128 for the five thermocouples attached to the liner in the same pattern as on the combustor rig test. Maximum temperatures were approximately 1500°F at the 8 o'clock circumferential position (240°) of the dilution hole plane.

In addition to the liner thermocouples, a liner thermal paint run at takeoff was performed. Photographs of the liner exterior are presented in Figures 129, 130, and 131, and an interior view of the thermal pattern in Figure 132. The highest temperature zones, just aft of each dilution hole, are represented in the color band of temperatures indicating 1400° to 1706°F. Two of the liner metal thermocouples were in these zones and indicated temperatures of 1440°F and 1480°F at takeoff conditions.

Exhaust Emissions

The baseline combustor exhaust-emissions testing was accomplished by making two separate steady-state measurement runs with emissions recorded at the seven operating conditions used for the LOH duty cycle analysis: ground idle (5 hp), operational idle (25 hp), 25, 40, 55, 75, and 100% power. Data were recorded in both ascending and descending power sequences, producing a total of twenty-six data points. A summary of the baseline combustor emissions data is presented in Table 81. Plots of CO, CH_x, NO_x, and smoke number as functions of output horsepower are presented in Figures 133 to 136. A plot of chemical versus mechanical fuel-air ratios is presented in Figure 137, which shows that the chemical fuel-air ratios were higher by an average of only 1.1% and, for the entire data set, varied from -5.92% to +6.72% about the corresponding mechanical values.

Figures 138 to 141 show shaft horsepower, CO_2, combustion efficiency, and fuel flow rate as functions of the chemical fuel-air ratio. These four curves, along with parts per million concentrations of CO, CH_x, and NO_x versus chemical fuel-air ratio, were used to compute the emission index

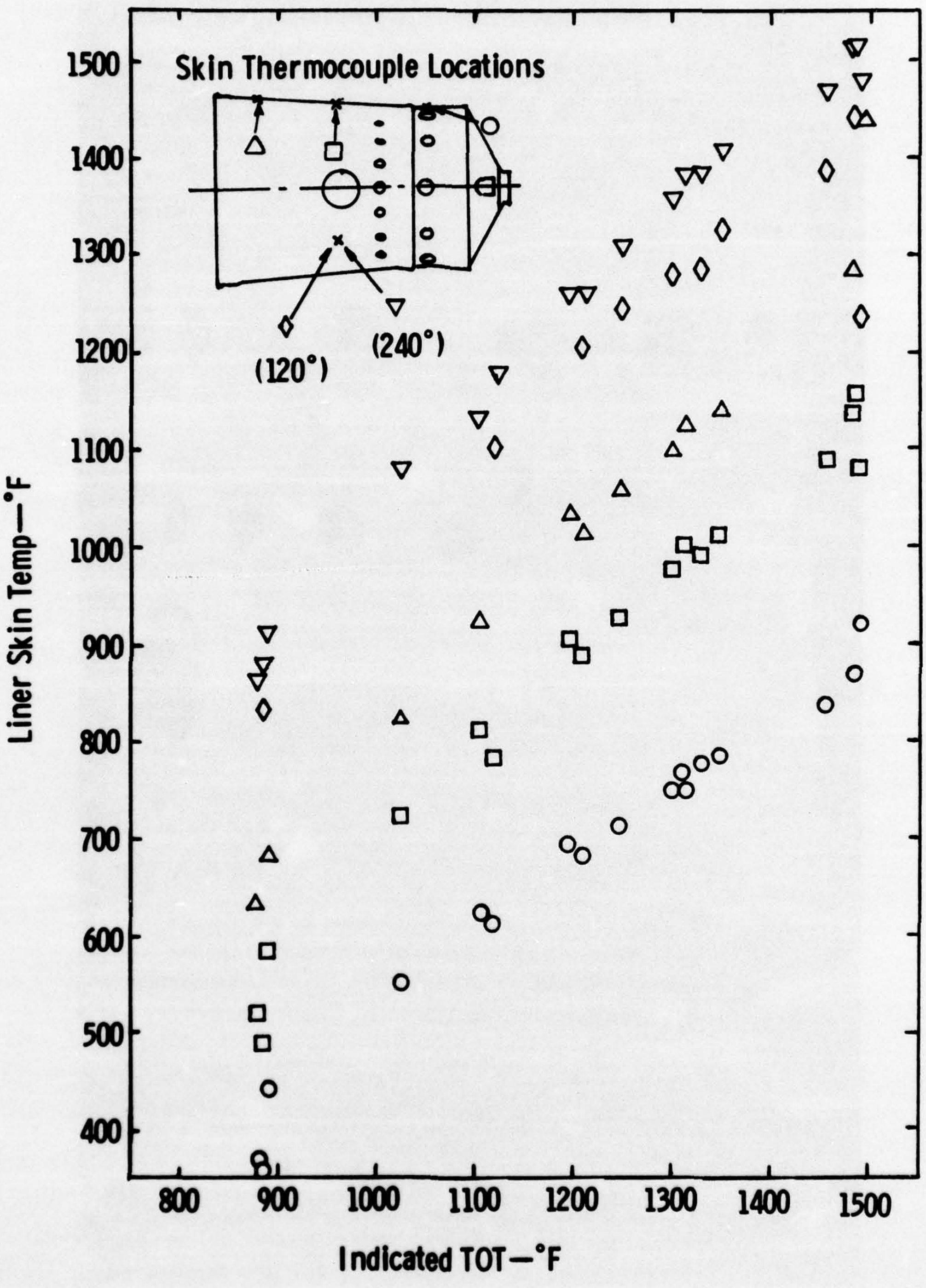


Figure 128. Baseline Liner Metal Temperatures from Engine Test.

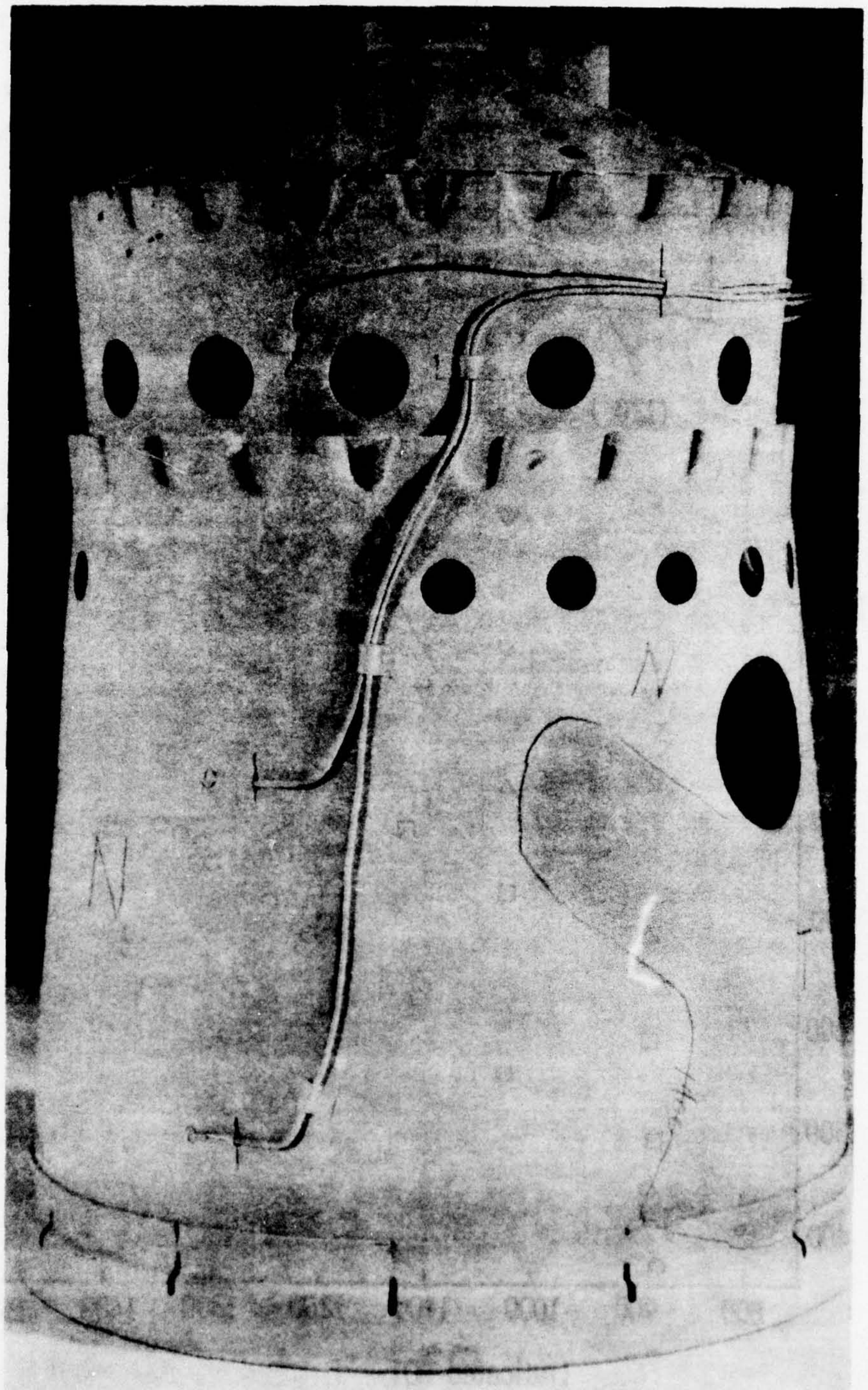


Figure 129. Baseline Liner Metal Temperature Pattern from Engine Test at 100% Power, External 270°-30° Rotation.

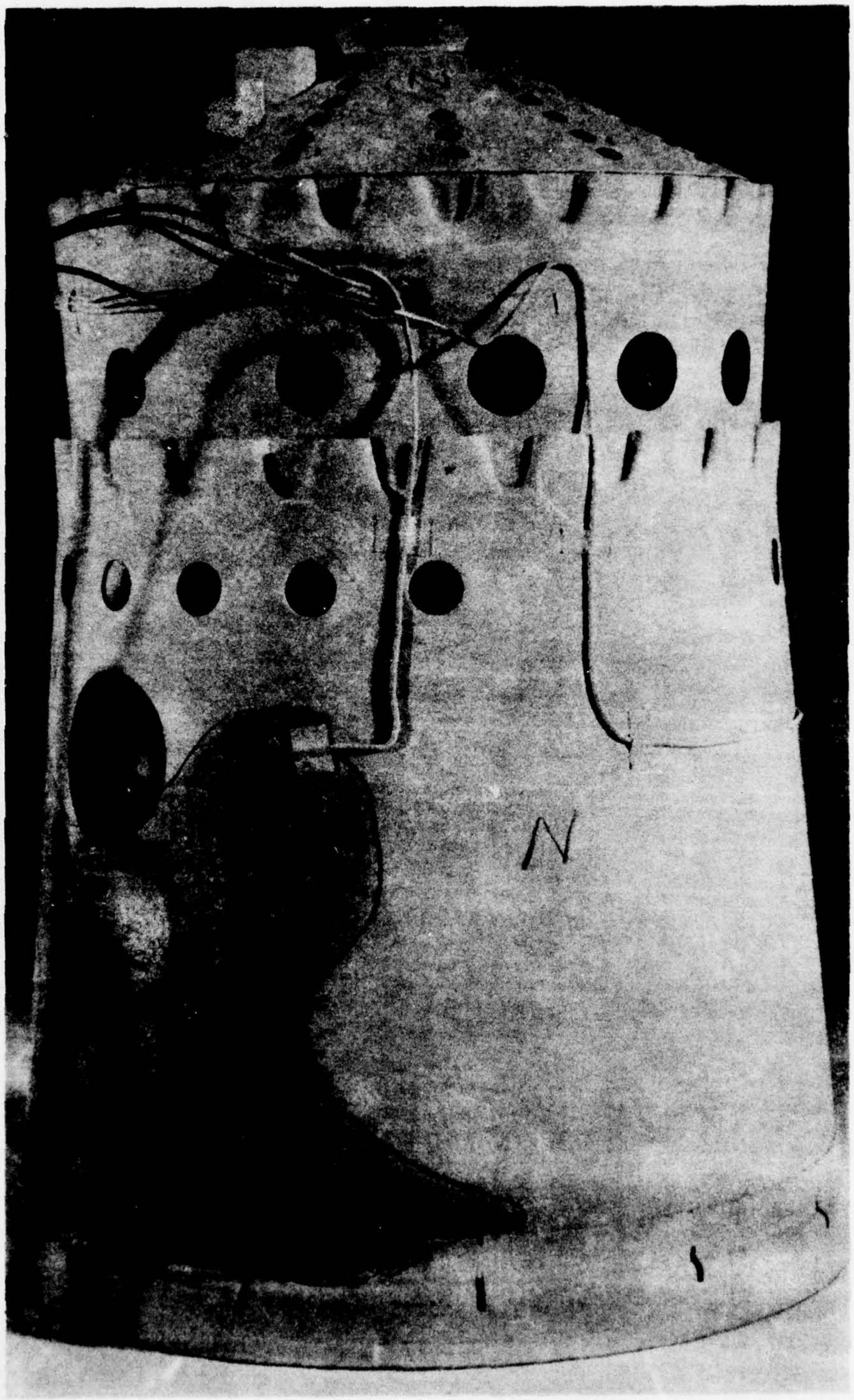


Figure 130. Baseline Liner Metal Temperature Pattern from Engine Test at 100% Power, External 150°-270° Rotation.

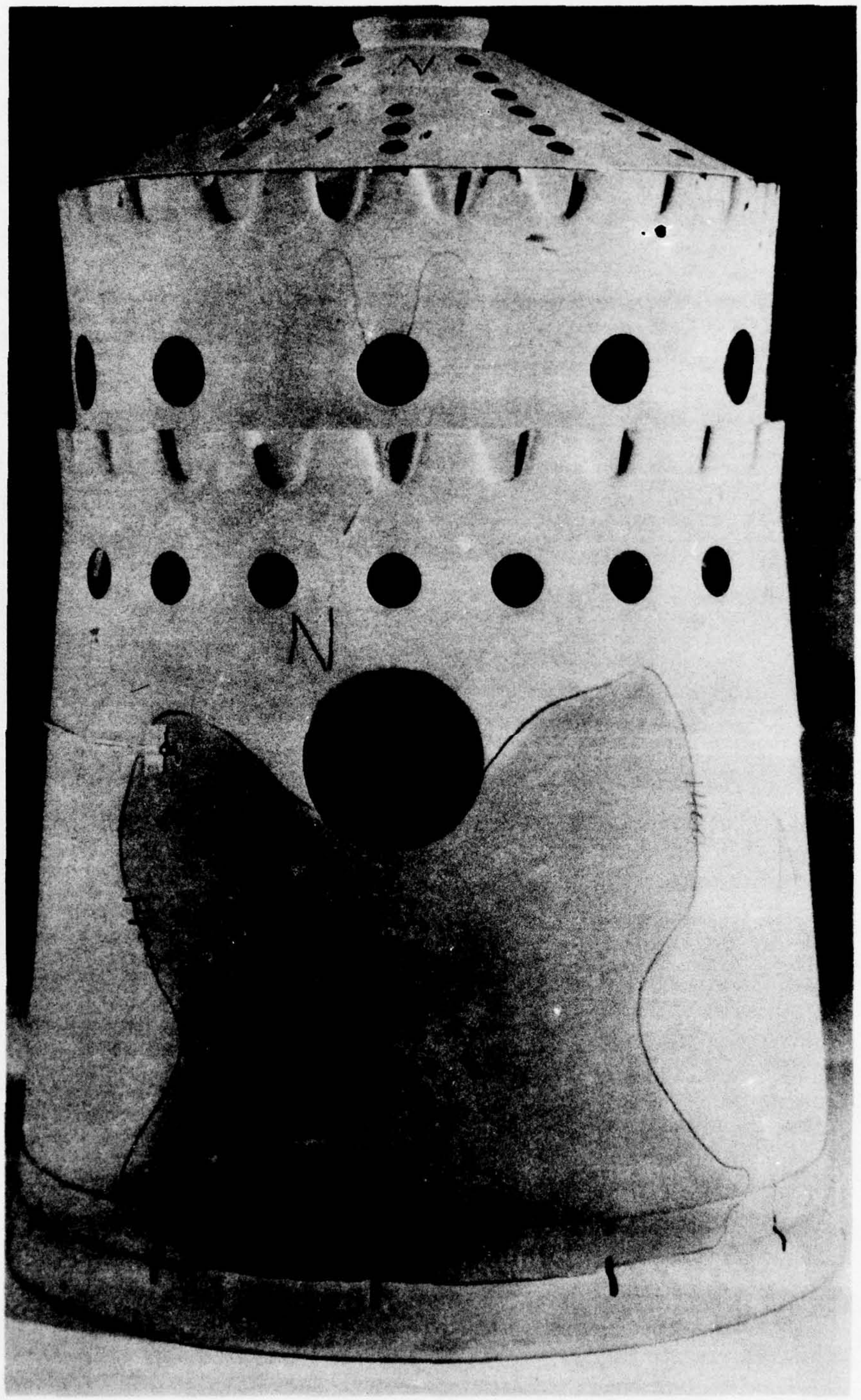


Figure 131. Baseline Liner Metal Temperature Pattern from Engine Test at 100% Power, External 30°-150° Rotation.

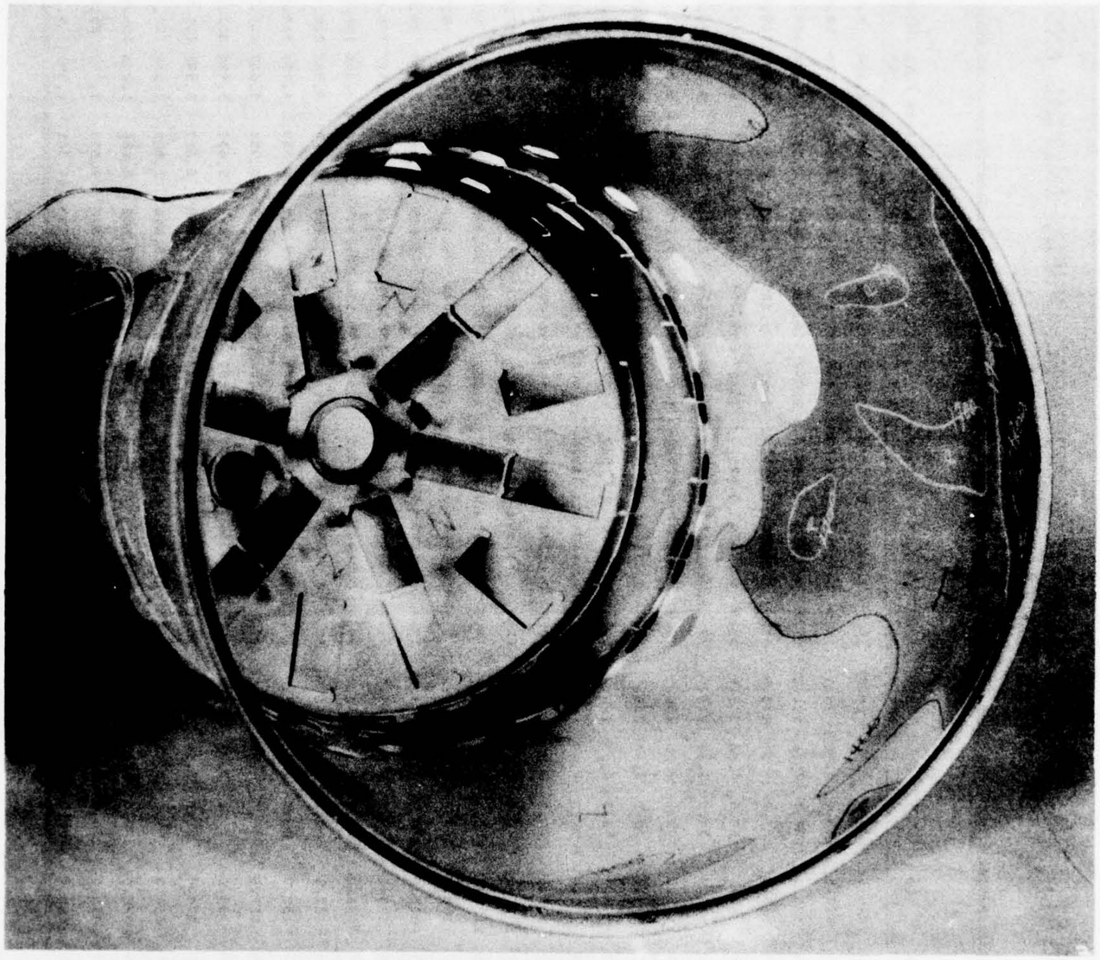


Figure 132. Baseline Liner Metal Temperature Pattern from Engine Test at 100% Power, Internal.

TABLE 81. BASELINE LINER, JP-4 REFERENCE FUEL, INITIAL ENGINE TEST SERIES DATA.

RDG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
232.	16.0	1040.0	275.0	2.30	69.9	5.0	0.01195	0.01130	1.058	96.882	85.143	12.892	2.152	4.2	1.0
233.	19.5	890.0	265.0	2.40	79.1	9.0	0.01237	0.01180	1.048	97.300	70.430	12.008	2.535	28.8	6.8
234.	31.8	575.0	107.0	2.76	116.0	21.0	0.01393	0.01450	0.961	98.665	40.471	4.313	3.676	109.1	26.0
235.	38.3	375.0	63.0	3.01	141.5	30.0	0.01506	0.01510	0.997	99.208	24.445	2.352	4.101	169.3	40.3
236.	42.6	268.0	48.0	3.35	167.4	35.0	0.01670	0.01580	1.057	99.473	15.776	1.618	4.119	229.3	54.6
237.	56.0	173.0	30.0	3.63	205.5	39.0	0.01805	0.01800	1.003	99.676	9.434	0.937	5.016	310.6	73.9
238.	78.0	113.0	33.5	4.25	256.9	42.0	0.02115	0.02090	1.012	99.772	5.275	0.895	5.980	411.5	98.0
239.	56.5	174.0	33.0	3.63	205.5	39.0	0.01805	0.01800	1.003	99.666	9.488	1.030	5.060	308.8	73.5
240.	44.0	263.0	35.5	3.25	166.4	34.0	0.01619	0.01580	1.025	99.501	15.962	1.234	4.386	226.1	53.8
241.	37.0	381.0	41.0	2.99	141.0	29.0	0.01495	0.01520	0.983	99.266	25.013	1.541	3.990	166.9	39.7
242.	29.9	565.0	71.0	2.72	115.0	22.0	0.01371	0.01450	0.945	98.791	40.405	2.907	3.512	105.8	25.2
243.	19.2	1010.0	320.0	2.28	78.6	11.0	0.01186	0.01180	1.005	96.728	83.321	15.117	2.602	27.8	6.6
244.	16.8	1125.0	433.0	2.17	69.4	8.0	0.01143	0.01120	1.020	95.892	96.288	21.222	2.362	5.0	1.2
245.	18.5	1150.0	443.0	2.21	69.2	9.0	0.01164	0.01130	1.030	95.875	96.620	21.313	2.553	5.0	1.2
246.	17.5	975.0	230.0	2.38	78.0	11.0	0.01229	0.01170	1.051	97.268	77.619	10.485	2.288	29.4	7.0
247.	23.5	600.0	94.0	2.78	115.0	22.0	0.01403	0.01440	0.975	98.685	41.917	3.760	2.697	106.6	25.4
248.	33.5	408.0	65.0	2.97	141.0	29.0	0.01487	0.01510	0.985	99.150	26.919	2.380	3.630	168.1	40.0
249.	41.0	282.0	42.0	3.33	166.9	35.0	0.01660	0.01600	1.038	99.469	16.695	1.424	3.987	228.4	54.4
250.	55.0	187.0	33.0	3.78	206.0	39.0	0.01881	0.01810	1.039	99.665	9.791	0.989	4.730	310.4	73.9
251.	74.0	117.0	36.0	4.30	255.5	42.0	0.02141	0.02090	1.024	99.766	5.397	0.951	5.607	415.7	99.0
252.	52.0	185.0	34.0	3.73	203.2	39.0	0.01856	0.01790	1.037	99.661	9.815	1.033	4.532	307.6	73.2
253.	41.5	270.0	66.0	3.36	167.4	33.0	0.01676	0.01600	1.047	99.420	15.838	2.217	3.998	227.0	54.1
254.	33.0	380.0	47.0	2.93	139.0	26.0	0.01465	0.01530	0.958	99.235	25.446	1.802	3.630	165.1	39.3
255.	27.5	575.0	72.0	2.83	115.0	20.0	0.01426	0.01450	0.984	98.819	39.542	2.835	3.106	104.9	25.0
256.	17.0	985.0	220.0	2.43	77.3	8.0	0.01254	0.01170	1.072	97.343	76.878	9.833	2.179	28.8	6.9
257.	15.6	1065.0	360.0	2.30	69.4	8.0	0.01201	0.01120	1.072	96.501	86.797	16.801	2.088	4.7	1.1

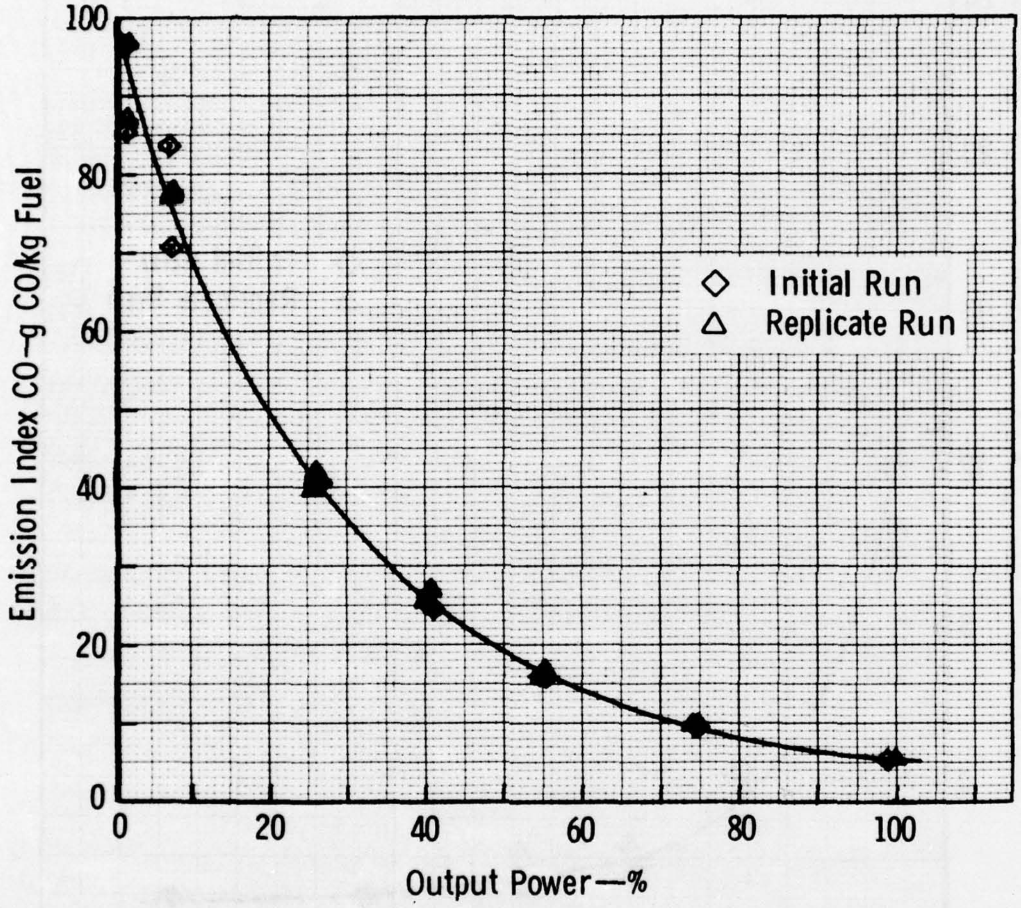


Figure 133. Baseline Liner Initial Engine Carbon Monoxide Emissions.

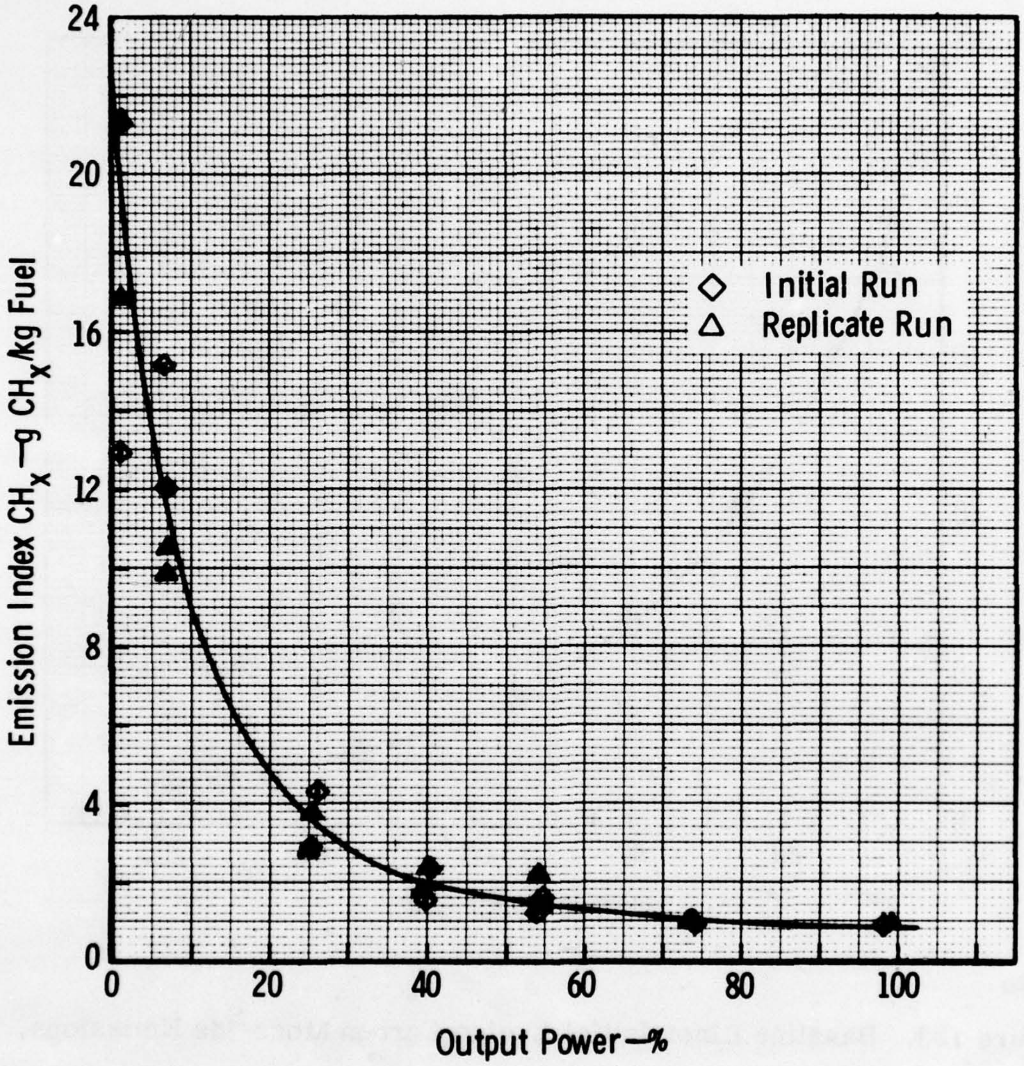


Figure 134. Baseline Liner Initial Engine Unburned Hydrocarbon Emissions.

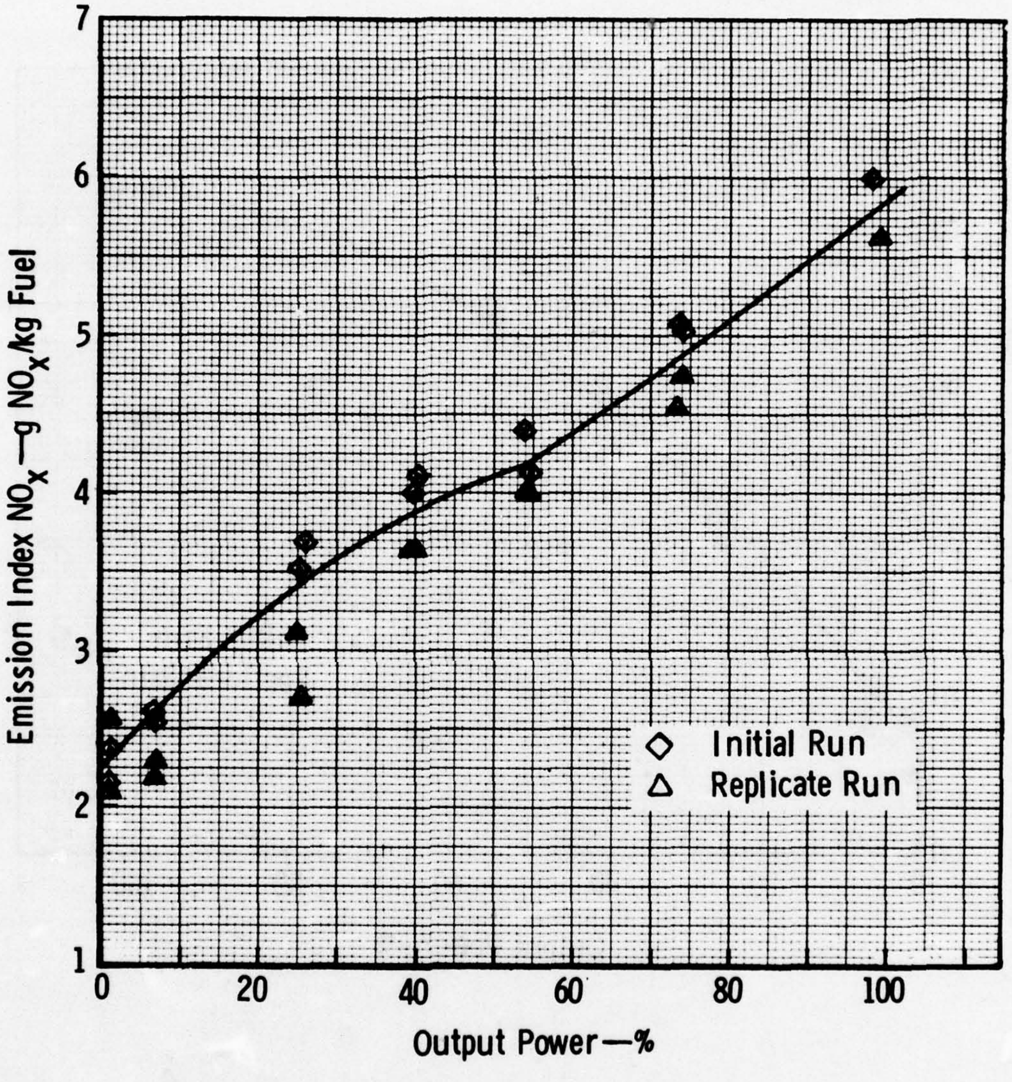


Figure 135. Baseline Liner Initial Engine Total Nitrogen Oxide Emissions.

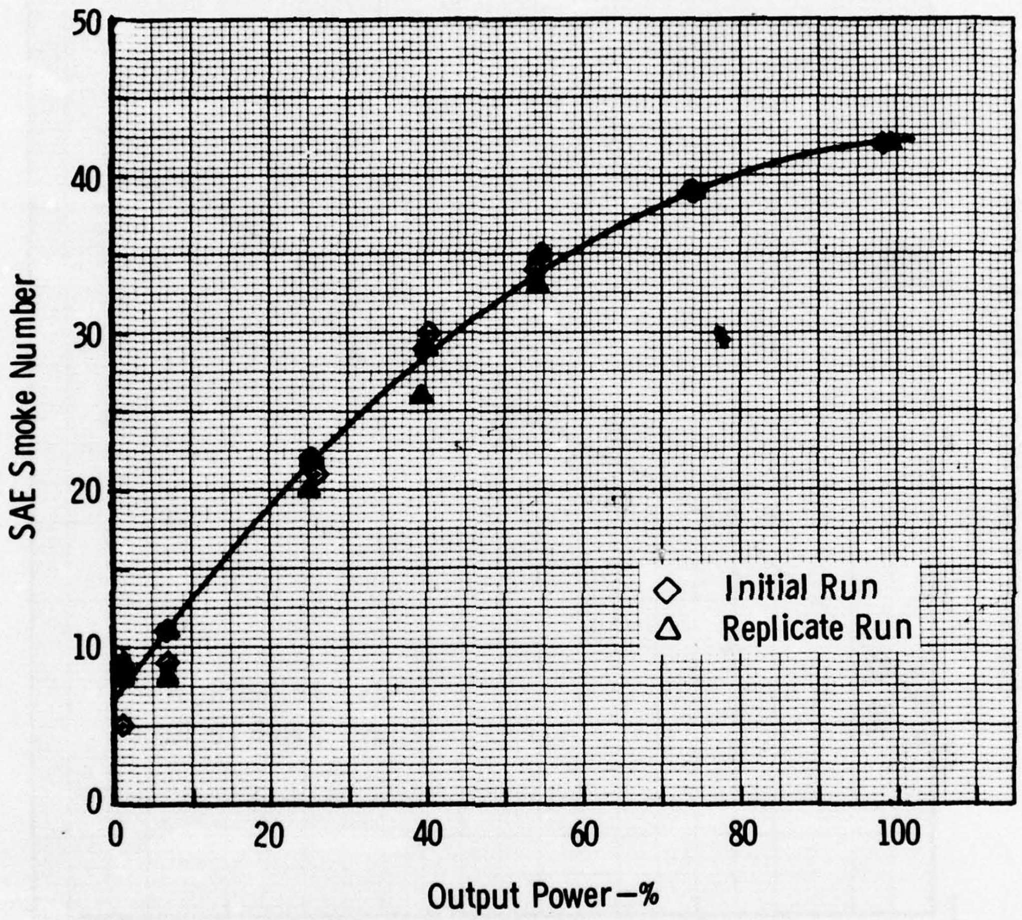


Figure 136. Baseline Liner Initial Engine Smoke.

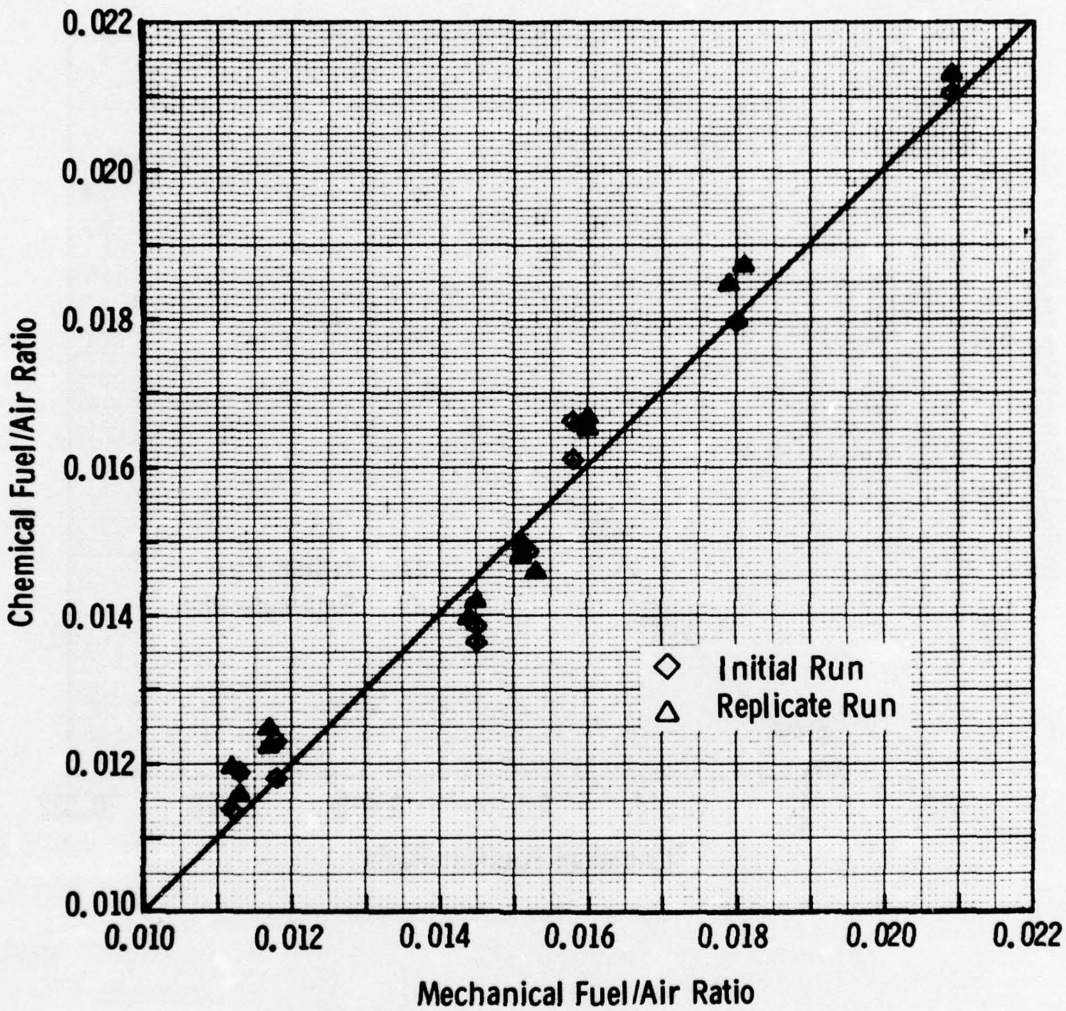


Figure 137. Baseline Liner Initial Engine Mechanical and Chemical Fuel-to-Air Ratios.

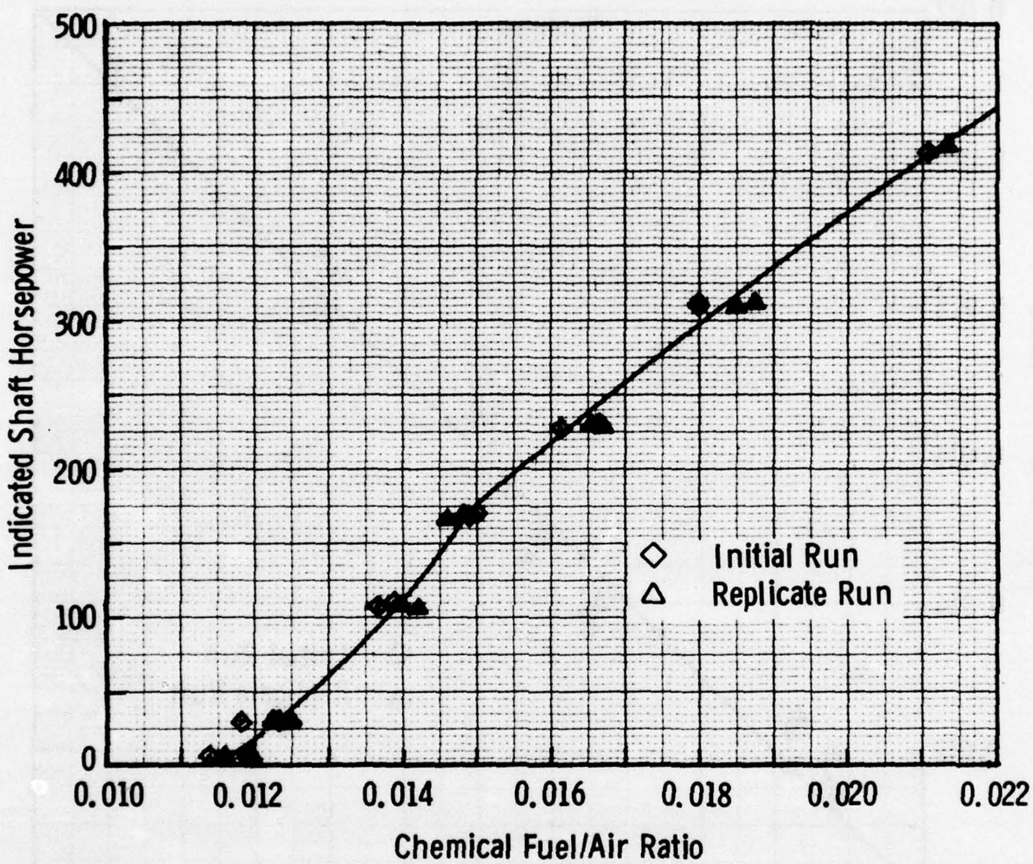


Figure 138. Baseline Liner Initial Engine Shaft Horsepower at Chemical Fuel-to-Air Ratios.

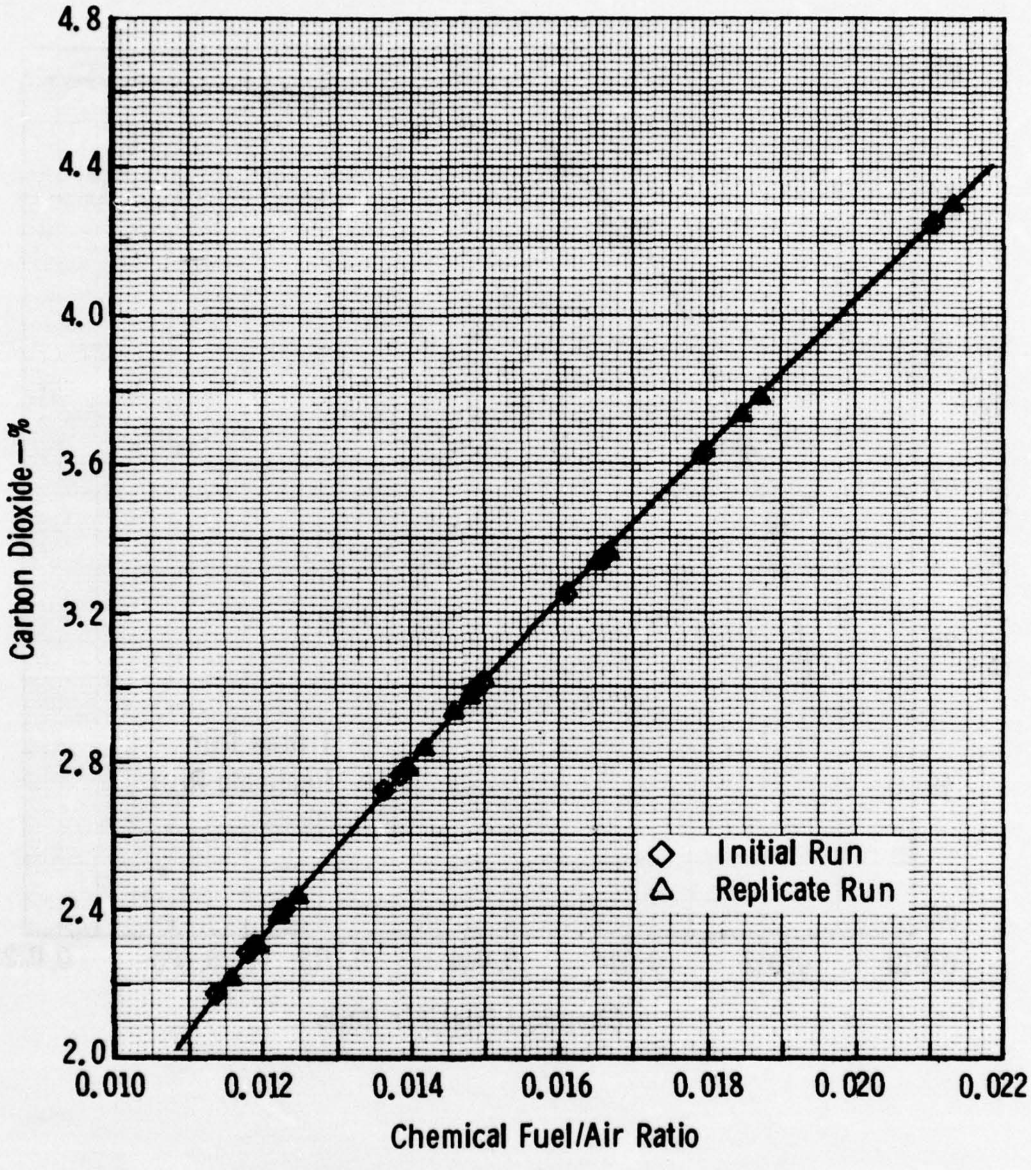


Figure 139. Baseline Liner Initial Engine Carbon Dioxide at Chemical Fuel-to-Air Ratios.

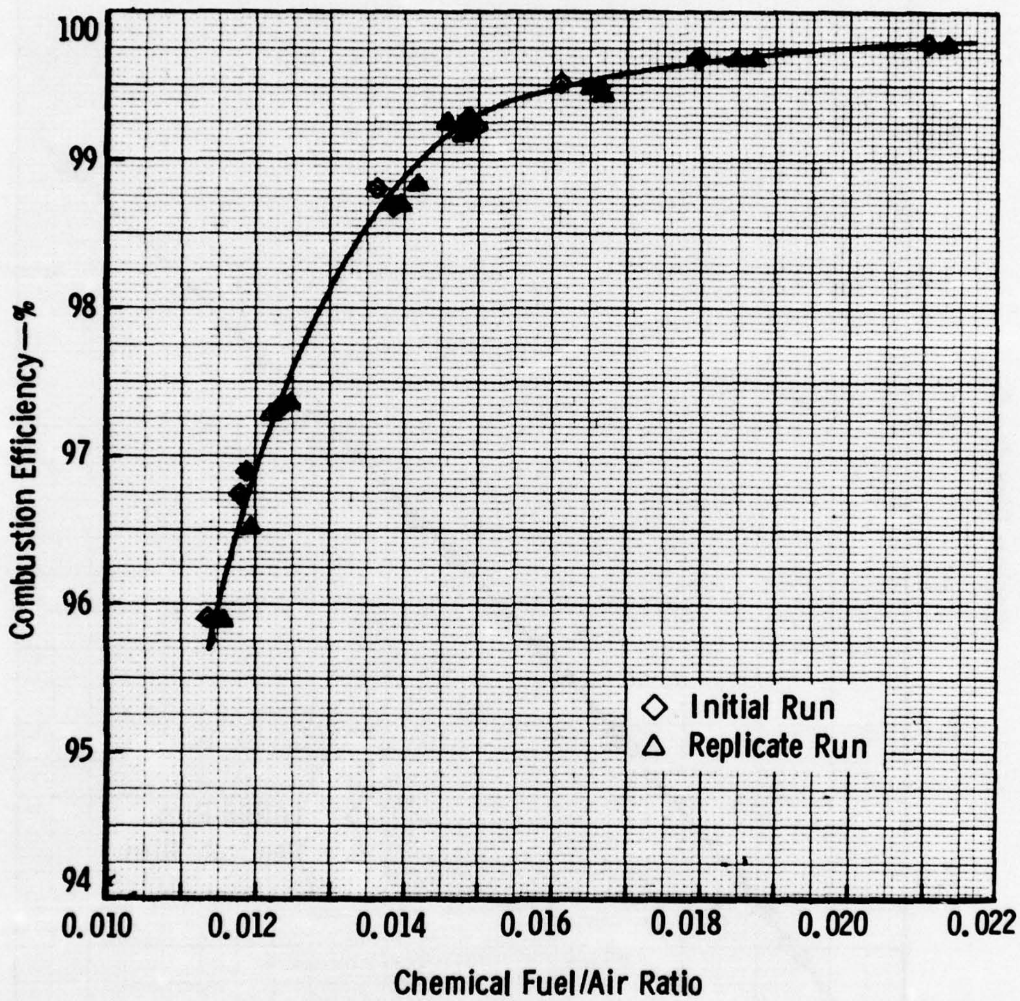


Figure 140. Baseline Liner Initial Engine Combustion Efficiency at Chemical Fuel-to-Air Ratios.

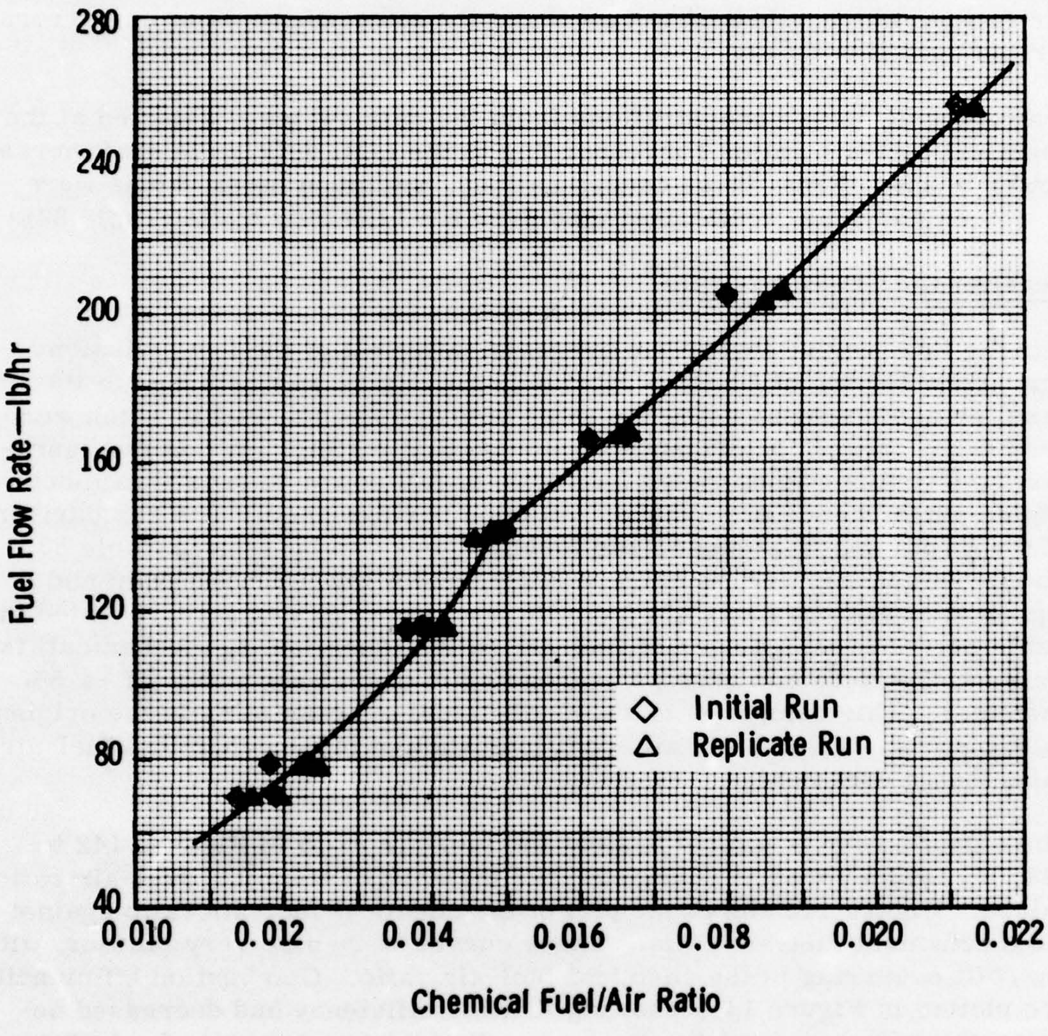


Figure 141. Baseline Liner Initial Engine Fuel Flow Rates at Chemical Fuel-to-Air Ratios.

curves presented above. The reason for this approach was the assumption that major sampling errors in the exhaust could be caused by the uneven distribution of combustor inlet air (through dilution holes) and primary zone combustion products. Gas samples in the exhaust that have high concentrations of pollutants and CO_2 will compute high chemical fuel-air ratios, which will tend to cancel out the effect of the sampling errors for the emission index.

Average emissions concentrations from the data set were selected at the chemical fuel-air ratios corresponding to the LOH duty cycle shaft horsepower levels. From these concentrations, emission index values were computed and time-weight averaged over the LOH duty cycle (Table 82).

Recalibration Data Analysis

For the final engine test in the program, after all of the low emissions combustor testing had been performed, the engine was returned to its baseline configuration using the same combustor components which were used in the initial performance documentation testing. In this configuration, the engine was operated from idle to full power to recalibrate both engine performance and exhaust emission performance. The comparison of the initial and final engine run fuel analyses can be seen in Table 83. The final fuel sample was more volatile, had a lower smoke point and higher aromatics. Test data from the recalibration run are presented in Table 84. The comparison of fuel-air ratios (chemical to mechanical) is shown in Table 85 and gave an average ratio of fuel-air ratios of +4.5% chemical. This compares to +1.1% chemical oversampling in the original baseline test. Effectively all conditions showed higher chemical fuel-air ratio than mechanical.

The output power is plotted against the fuel-air ratio in Figures 142 to 144, showing almost no change beyond the shift of chemical fuel-air ratio values. Figure 145 shows the plot of the chemical fuel-air ratio against the mechanical fuel-air ratio. These curves were also very similar, with the shift occurring in the chemical fuel-air ratio. Combustion efficiencies are plotted in Figure 146, showing that the efficiency had decreased between the initial run and the final run. Emission index plots for hydrocarbon, carbon monoxide, and nitrogen oxides are plotted against percent output power in Figures 147 through 149. Unburned hydrocarbons and nitrogen oxides showed no detectable change, but carbon monoxide emissions increased in the final run, thus explaining the drop in combustion efficiency. Exhaust smoke also increased about five smoke numbers in all conditions, probably due to the higher aromatics and lower smoke point noted in the fuel sample analysis.

TABLE 82. BASELINE LINER, JP-4 REFERENCE FUEL, INITIAL ENGINE TEST SERIES DATA.

BASELINE LINER, 6871486, JP-4 REFERENCE FUEL, APRIL ENGINE TEST SERIES DATA

RDG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
1.	16.5	1110.0	365.0	2.25	70.0	6.8	0.01178	0.00000	0.000	96.328	92.163	17.354	2.250	5.0	1.2
6.	18.0	980.0	265.0	2.37	78.0	9.8	0.01226	0.00000	0.000	97.111	78.205	12.110	2.359	25.0	6.0
25.	26.0	590.0	88.0	2.77	116.0	20.5	0.01398	0.00000	0.000	98.715	41.387	3.535	2.996	105.0	25.0
40.	34.0	385.0	53.0	3.04	143.0	28.4	0.01521	0.00000	0.000	99.235	24.852	1.959	3.605	168.0	40.0
55.	43.5	270.0	39.0	3.12	170.0	34.5	0.01554	0.00000	0.000	99.460	17.058	1.411	4.514	231.0	55.0
75.	56.5	175.0	33.0	3.71	209.0	39.2	0.01846	0.00000	0.000	99.672	9.337	1.008	4.952	315.0	75.0
100.	76.5	120.0	41.0	4.31	262.0	42.1	0.02146	0.00000	0.000	99.751	5.522	1.080	5.782	420.0	100.0

BASELINE LINER, 6871486, JP-4 REFERENCE FUEL, APRIL ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	-I TOTAL	SMOKE NO
1.	0.00	70.00	17.354	92.163	2.250	111.767	6.80
6.	0.15	78.00	12.110	78.205	2.359	92.674	9.80
25.	0.00	116.00	3.535	41.387	2.996	47.918	20.50
40.	0.15	143.00	1.959	24.852	3.605	30.416	28.40
55.	0.45	170.00	1.411	17.058	4.514	22.983	34.50
75.	0.20	209.00	1.008	9.337	4.952	15.297	39.20
100.	0.05	262.00	1.080	5.522	5.782	12.384	42.10
CYCLE TOTALS		164.55	2.114	19.542	4.454	26.111	42.10
PERCENT OF BASELINE		100.00	100.00	100.00	100.00	100.00	

TABLE 83. FUEL SAMPLE PROPERTIES FOR JP-4 REFERENCE FUEL MIL-T-5161G (GRADE I).

Parameter	Sample Results Initial	Sample Results Final	Specification
Distillation			
I.B.P., °F	140	168	
5% recovered, °F	208	202	
10%	226	211	
20%	246	223	
30%	265	238	
40%	283	254	
50%	305	274	
60%	333	298	
70%	365	325	
80%	396	355	
90%	431	398	
95%	454	454	
End Point, °F	471	489	450 max
Recovered, %	98.3	98.0	
Residue, %	1.2	1.0	1.5 max
Loss, %	0.5	1.0	1.5 max
10% evap., °F	224	209	200 max
20%	245	222	180-230
50%	304	272	230-275
90%	429	394	325-370
Gravity, °API	54.2	52.1	50.0-57.0
Aniline Point, °F	136.8	108.7	
Aniline-Gravity Product	7415	5663	
Net Heat of Combustion BTU/lb (Calculated)	18,758	18,557	18,400-18,750
Reid Vapor Pressure, psi	2.0	2.0	2.0-3.0
Smoke Point, mm	25.5	22.0	
Flash Point, °F			
Corrosion, Copper Strip	1a	1a	1b max
Sulfur, % by wt.	0.02	0.12	0.15-0.40
Hydrogen, % by wt.	14.643	13.988	
H/C Atom Ratio	2.044	1.938	
Aromatics, % by vol.	14.0	22.5	10.0-25.0
Olefins, % by vol.		1.4	5.0 max

TABLE 84. BASELINE LINER, JP-4 REFERENCE FUEL, FINAL ENGINE TEST SERIES DATA.

RDG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
354.	17.2	1680.0	390.0	2.28	65.2	11.0	0.01213	0.01123	1.080	95.242	135.501	18.012	2.279	10.2	2.4
355.	17.5	1810.0	420.0	2.40	67.1	14.0	0.01281	0.01159	1.105	95.141	138.417	18.392	2.198	28.6	6.8
356.	28.0	700.0	110.0	2.83	113.7	27.0	0.01423	0.01435	0.992	98.476	48.235	4.340	3.169	104.5	24.9
357.	36.0	470.0	60.5	3.10	139.4	34.0	0.01543	0.01519	1.016	99.089	29.900	2.204	3.762	166.8	39.7
358.	43.0	317.0	46.5	3.35	164.4	39.0	0.01659	0.01573	1.055	99.403	18.777	1.577	4.184	229.2	54.6
359.	57.0	206.0	36.0	3.70	203.8	43.0	0.01828	0.01782	1.026	99.620	11.095	1.110	5.043	314.9	75.0
360.	78.5	125.0	31.5	4.38	254.2	46.0	0.02165	0.02056	1.053	99.768	5.704	0.823	5.884	412.4	98.2
361.	55.5	210.0	32.0	3.69	201.8	43.0	0.01823	0.01775	1.027	99.625	11.341	0.990	4.923	312.2	74.3
362.	44.0	335.0	37.0	3.34	164.7	38.0	0.01655	0.01586	1.043	99.404	19.897	1.258	4.292	228.8	54.5
363.	37.0	465.0	47.0	3.08	137.8	33.0	0.01532	0.01505	1.018	99.133	29.789	1.724	3.893	166.5	39.6
364.	28.5	680.0	80.0	2.83	112.4	27.0	0.01421	0.01423	0.998	98.608	46.938	3.162	3.231	104.7	24.9
365.	19.4	1490.0	295.0	2.40	71.3	14.0	0.01259	0.01154	1.091	96.124	115.912	13.141	2.479	28.3	6.7
366.	18.2	1490.0	305.0	2.30	67.3	12.0	0.01210	0.01110	1.090	95.930	120.540	14.129	2.418	11.8	2.8

TABLE 85. BASELINE ENGINE RECALIBRATION, FUEL-AIR RATIO COMPARISON USING JP-4 REFERENCE FUEL

```
RATIO OF F/A C/M AVG = 1.046
               SIGMA = 0.037
      1  SIGMA RANGE = 1.009 1.083
      2  SIGMA RANGE = 0.972 1.120
      3  SIGMA RANGE = 0.935 1.156
```

RDG NO	FAC/FAM
356	0.9917
364	0.9984
357	1.0160
363	1.0182
359	1.0258
361	1.0270
362	1.0434
360	1.0529
358	1.0549
354	1.0805
366	1.0898
365	1.0906
355	1.1049

CHEMICAL PROPERTIES OF THE FUEL USED

C1 MOL WT	H/C	HC
13.964317	1.937816	18521.

Exhaust emissions from each engine run were time-weight averaged over the LOH duty cycle. These results are shown in Table 86, where the percentages are based upon the total cycle emissions values from the initial engine test. Emissions from the final baseline run were 15.6% higher in total emissions, which is a result of the combustor producing higher CO and CH_x with only a slight decrease in NO_x.

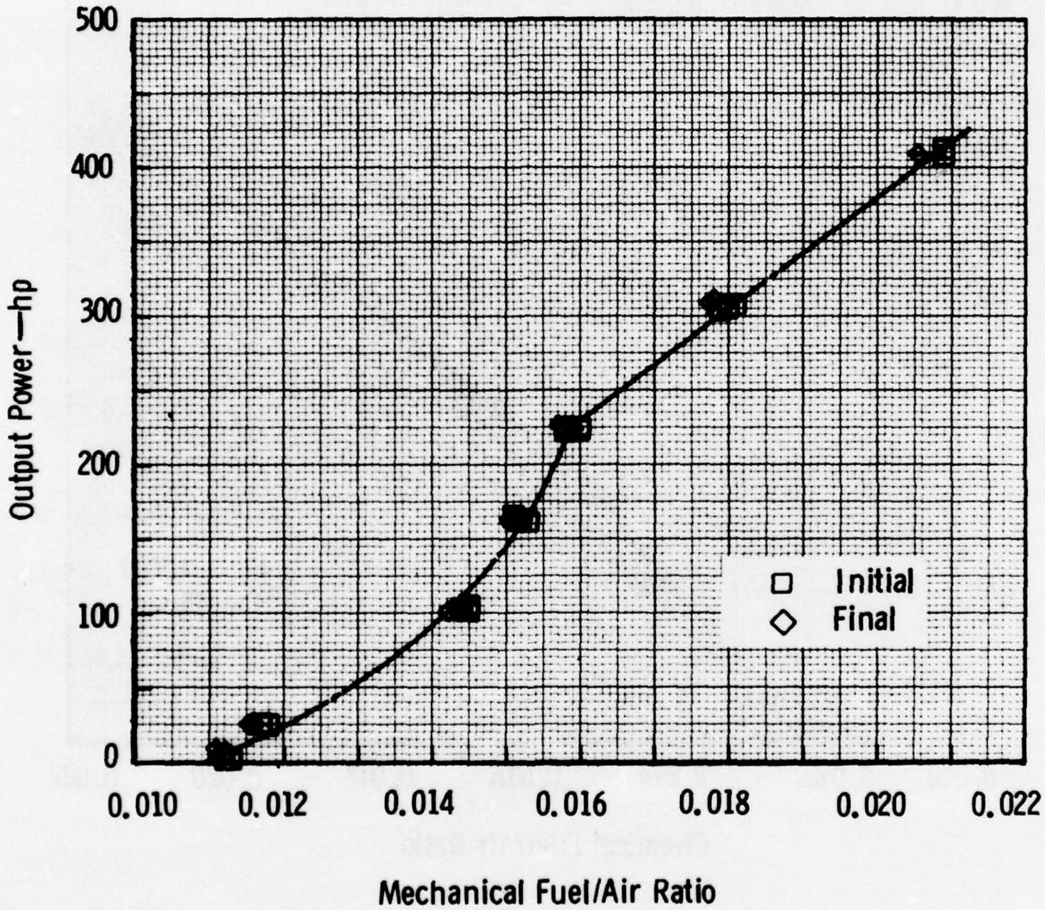


Figure 142. Baseline Liner Initial and Final Engine Shaft Horsepowers at Mechanical Fuel-to-Air Ratios.

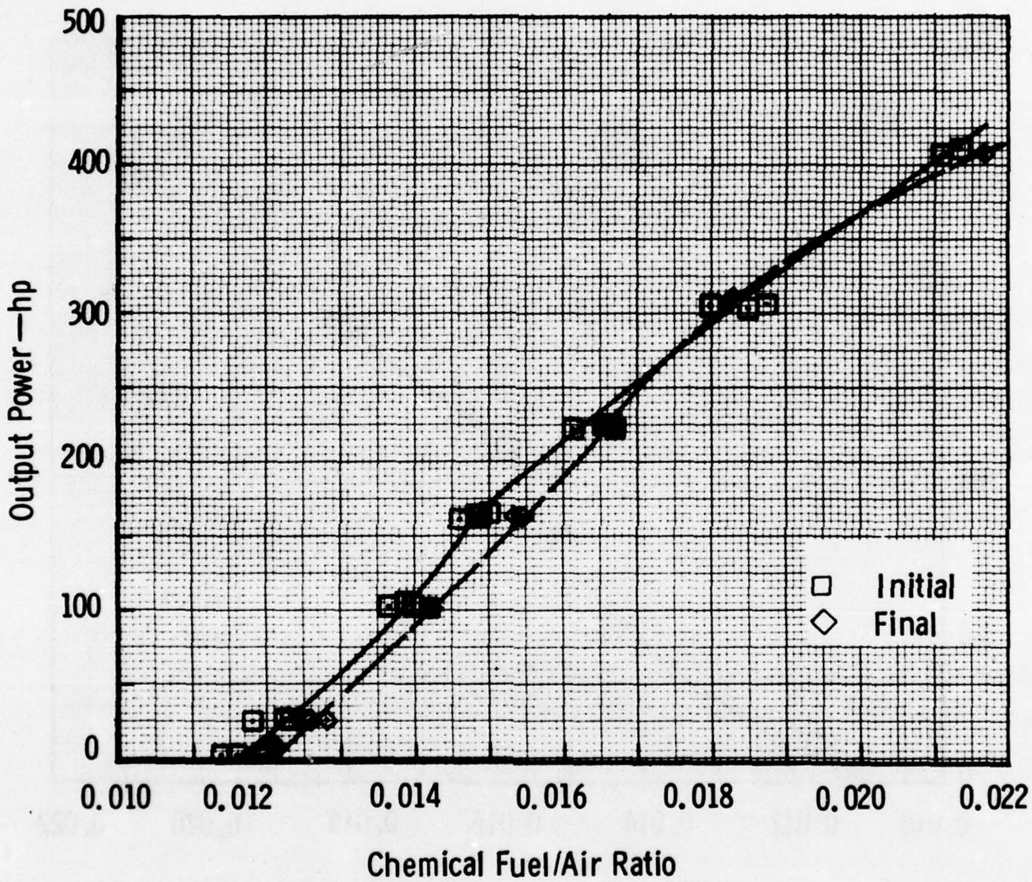


Figure 143. Baseline Liner Initial and Final Engine Shaft Horsepowers at Chemical Fuel-to-Air Ratios.

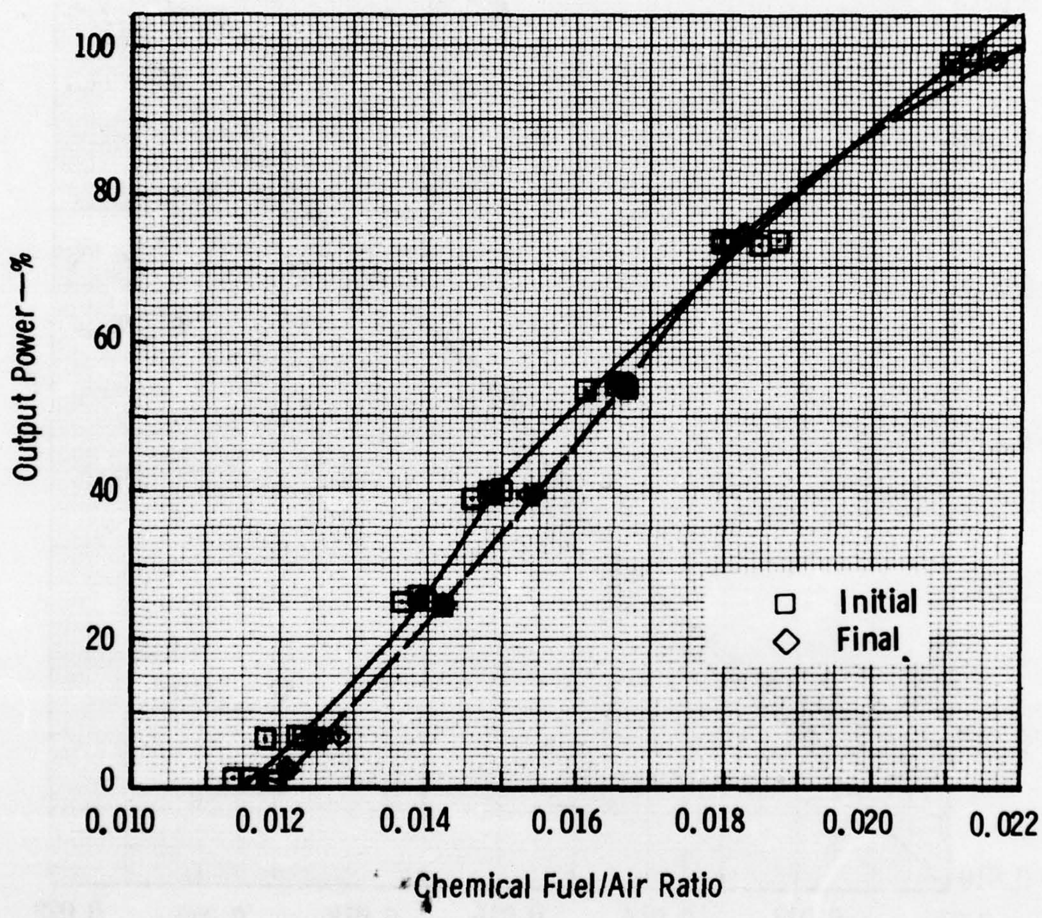


Figure 144. Baseline Liner Initial and Final Engine Shaft Horsepowers at Chemical Fuel-to-Air Ratios.

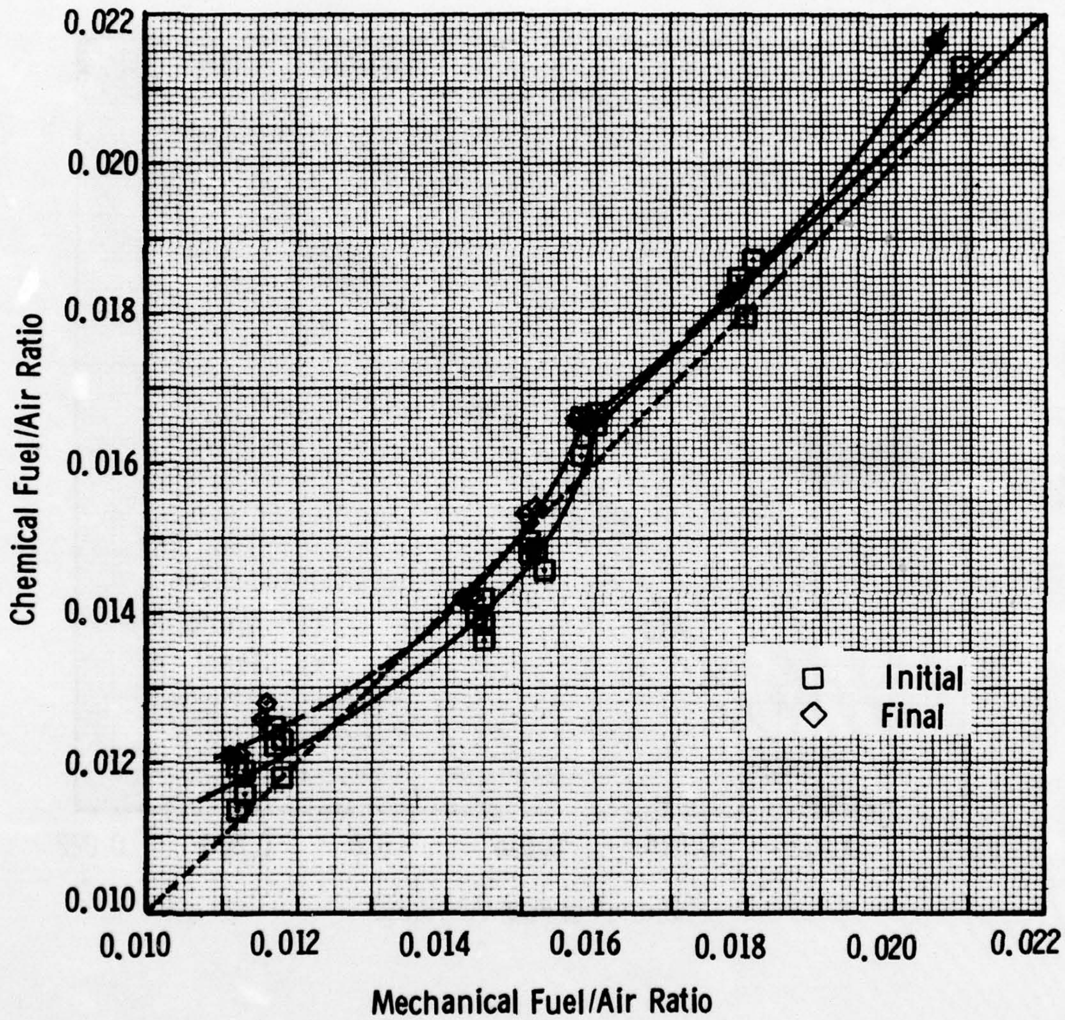


Figure 145. Baseline Liner Initial and Final Engine Mechanical and Chemical Fuel-to-Air Ratios.

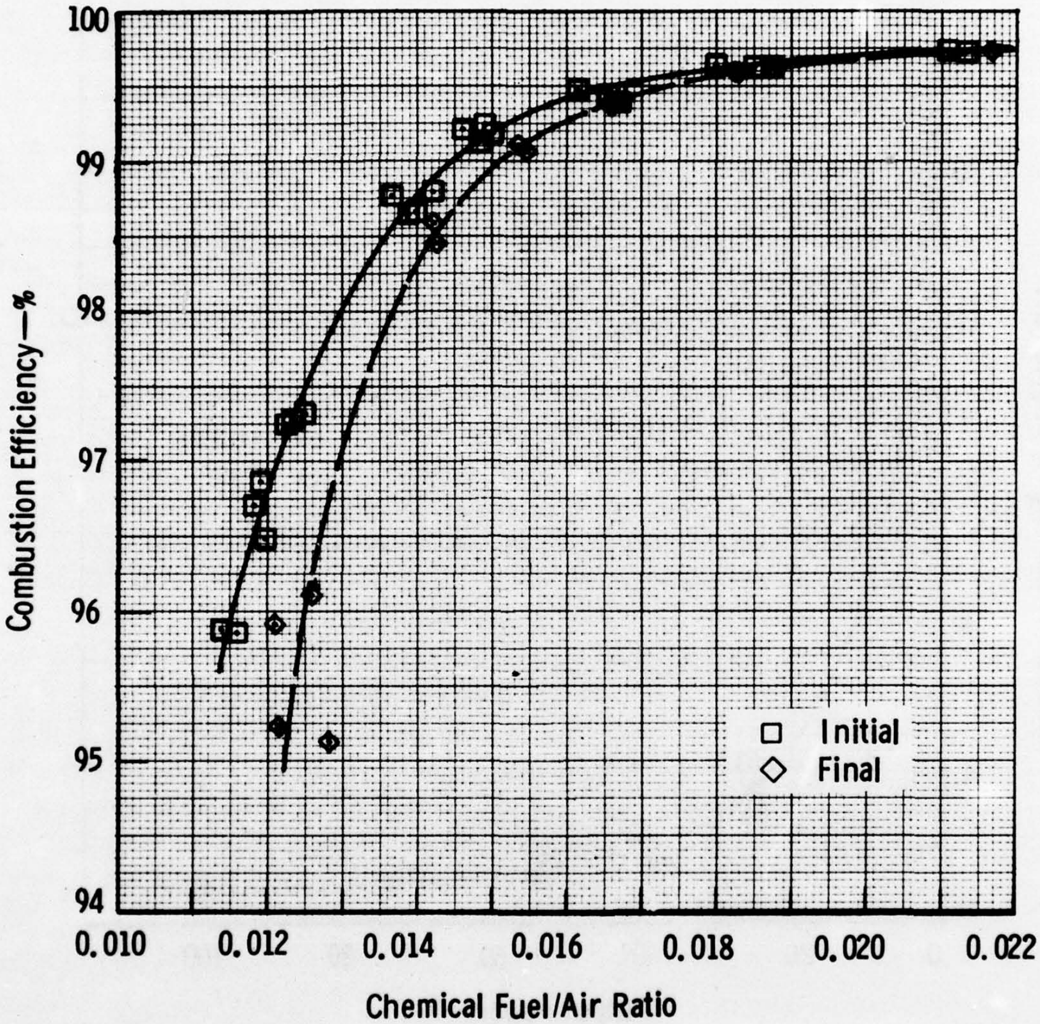


Figure 146. Baseline Liner Initial and Final Engine Combustion Efficiency at Chemical Fuel-to-Air Ratios.

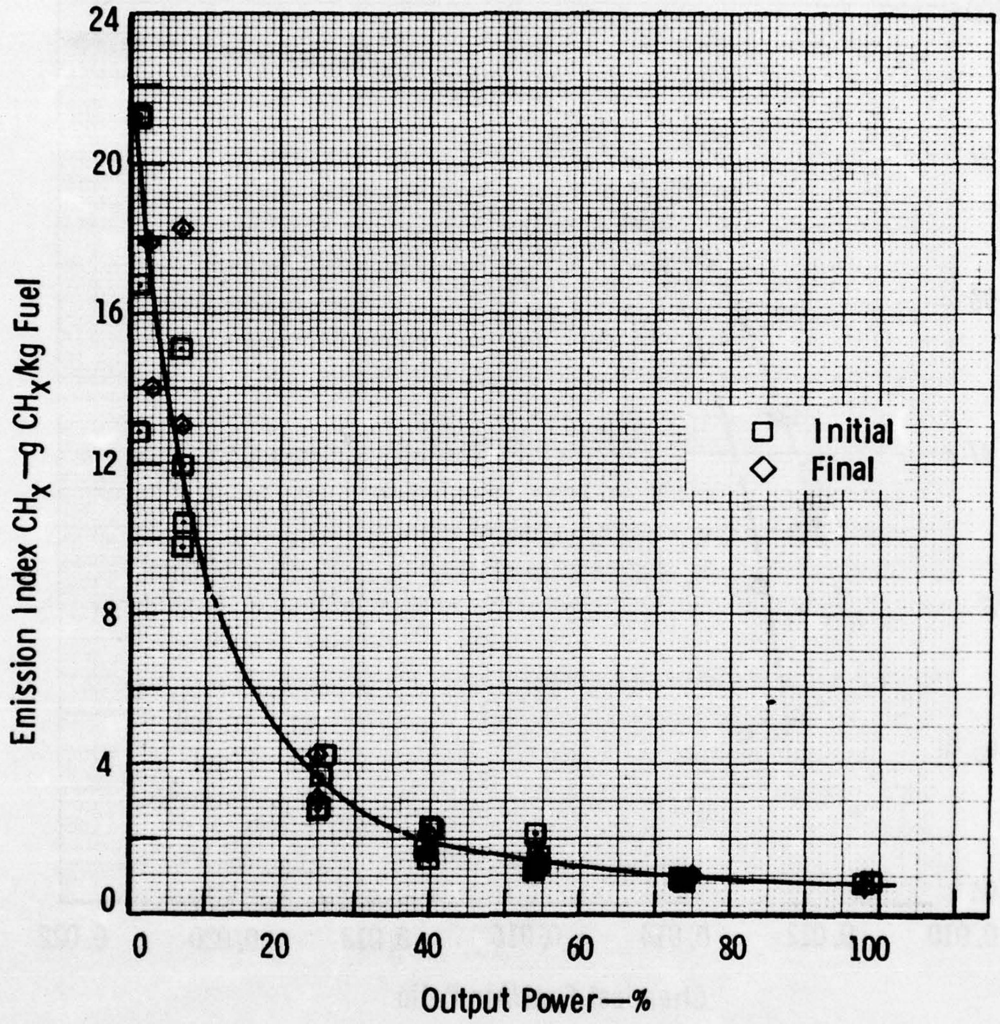


Figure 147. Baseline Liner Initial and Final Engine Unburned Hydrocarbon Emissions.

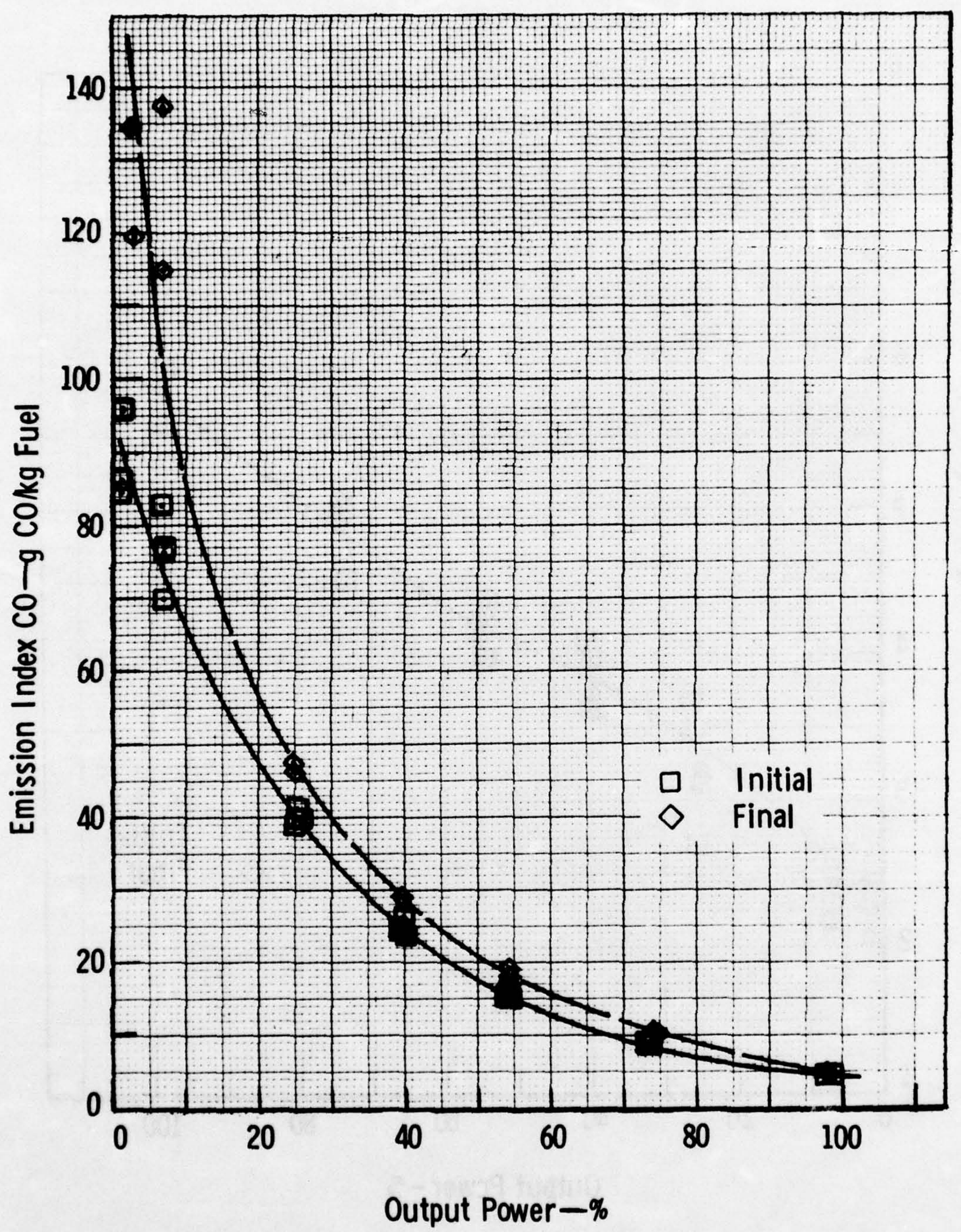


Figure 148. Baseline Liner Initial and Final Engine Carbon Monoxide Emissions.

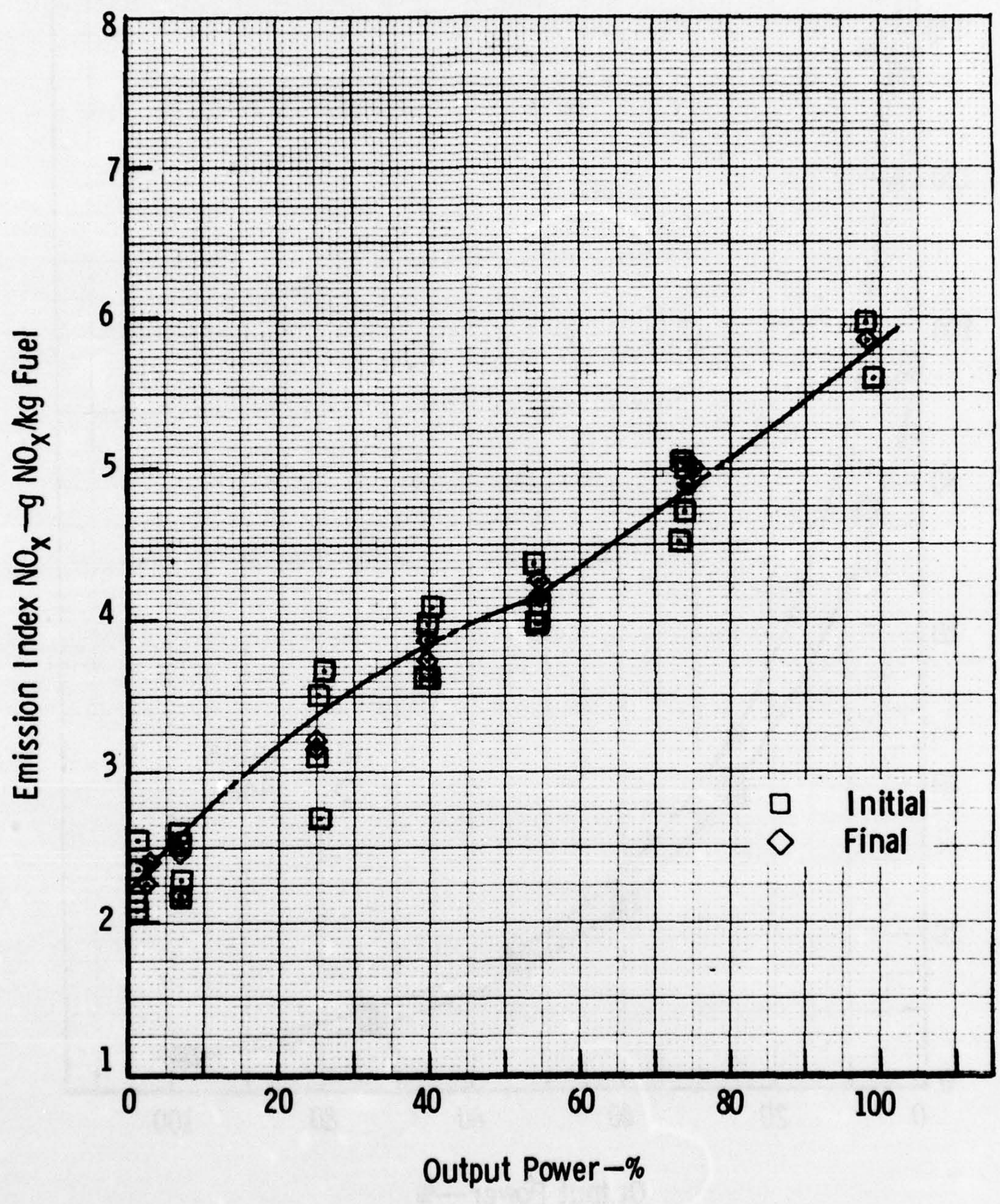


Figure 149. Baseline Liner Initial and Final Engine Total Nitrogen Oxide Emissions.

TABLE 86. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FROM ENGINE TEST OF BASELINE LINER.

BASELINE LINER, 6871486, JP-4 REFERENCE FUEL, APRIL ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	70.00	17.354	92.163	2.250	111.767	6.80
6.	0.15	78.00	12.110	78.205	2.359	92.674	9.80
25.	0.00	116.00	3.535	41.387	2.996	47.918	20.50
40.	0.15	143.00	1.959	24.852	3.605	30.416	28.40
55.	0.45	170.00	1.411	17.058	4.514	22.983	34.50
75.	0.20	209.00	1.008	9.337	4.952	15.297	39.20
100.	0.05	262.00	1.080	5.522	5.782	12.384	42.10
CYCLE TOTALS		164.55	2.114	19.542	4.454	26.111	42.10
PERCENT OF BASELINE		100.00	100.00	100.00	100.00	100.00	

BASELINE LINER, 6871486, JP-4 REFERENCE FUEL, JULY ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	65.00	18.717	145.267	2.320	166.304	11.00
6.	0.15	69.00	17.713	111.199	2.405	131.317	13.50
25.	0.00	113.00	3.621	47.429	3.184	54.234	27.00
40.	0.15	139.00	1.931	29.907	3.815	35.653	33.80
55.	0.45	166.00	1.497	19.305	4.273	25.075	38.50
75.	0.20	204.00	1.138	10.745	4.942	16.825	42.80
100.	0.05	259.00	0.849	5.391	5.977	12.217	46.10
CYCLE TOTALS		159.65	2.461	23.331	4.401	30.193	46.10
PERCENT OF BASELINE		97.02	116.37	119.39	98.81	115.63	

The performance of the engine was quite consistent between the initial and final runs considering that the engine underwent 112:44 hours of baseline and low emissions combustion testing.

PRECHAMBER COMBUSTOR

The low-emission prechamber combustion system delivered to the Model 250-C20B engine for engine testing is detailed in Table 87. This prechamber liner, No. 13, was the final development combustor liner tested on the combustor rig. The combustor outer case, liner, igniter, fuel nozzle, and the assembly are shown in Figures 150 through 155.

TABLE 87. LOW-EMISSIONS PRECHAMBER COMBUSTORS PARTS LIST FOR ENGINE TESTING

Part Name	Part Number
Outer Case	EX-114012
Liner	EX-116291
Igniter	EX-115299
Fuel System	
Nozzle	EX-115870C
Pressure Relief Valve	SS-4CPA2-50

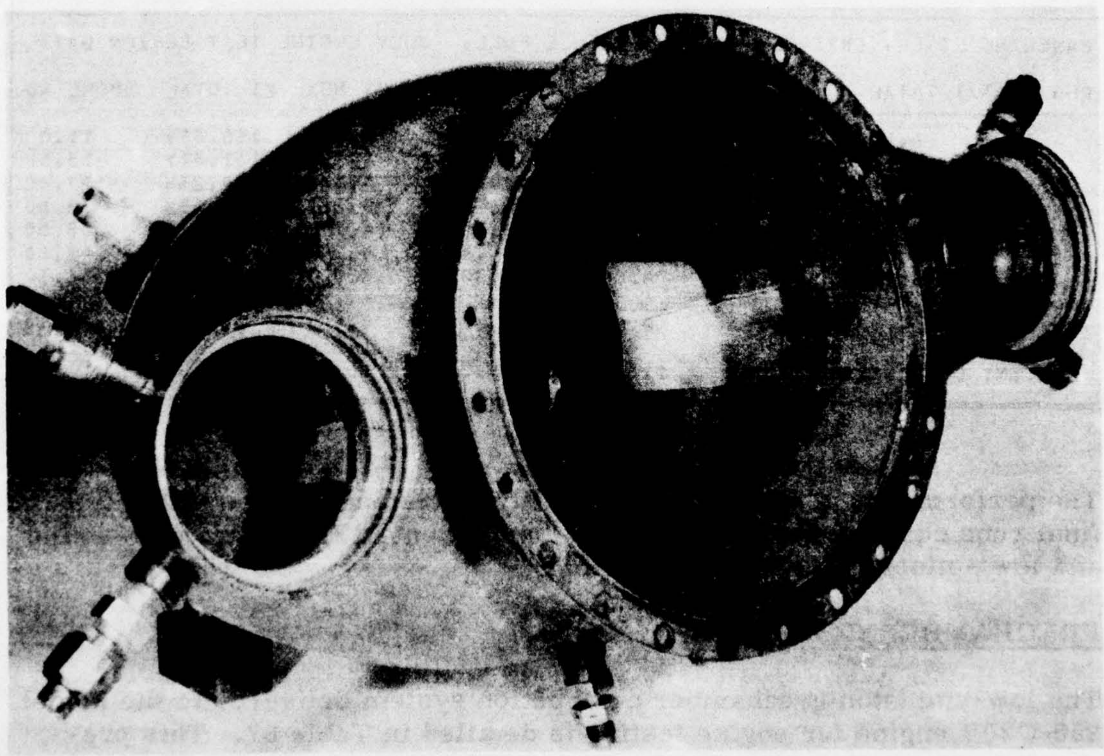


Figure 150. Prechamber Outer Combustion Case, EX-114012, Internal View.

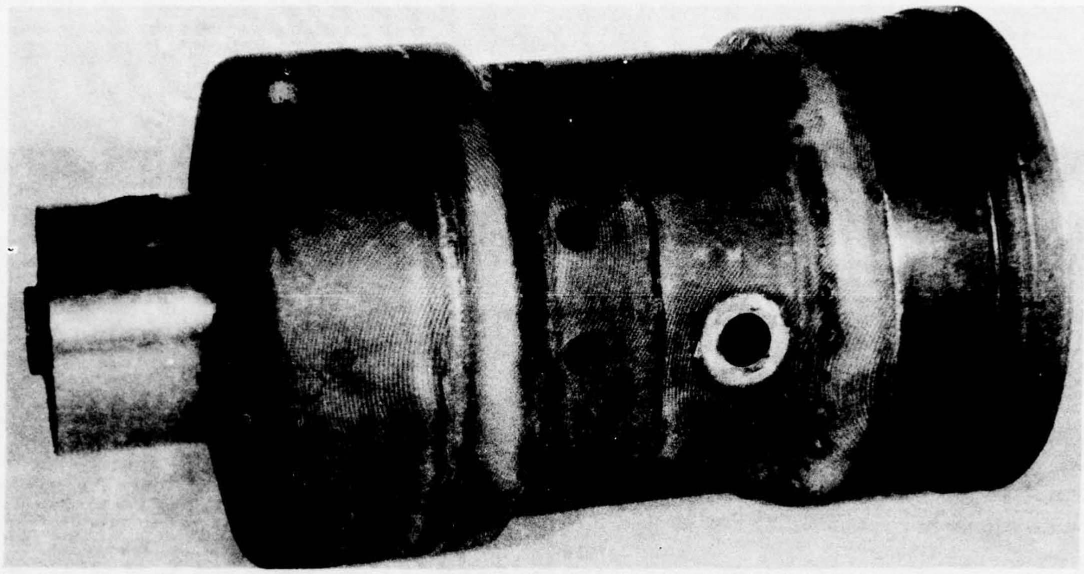


Figure 151. Prechamber Liner No. 13 (EX-116291).

Exhaust Temperature Profile

The first engine testing of the prechamber combustor system was a routine shakedown run followed by a combustor exhaust temperature profile run using the engine thermocouple instrumentation ring shown in Figure 120. The poor temperature profile measured from liner No. 13 led to a series of four more liner configurations before the next phase of the testing could be initiated. Changes to the prechamber liners were restricted to the dilution zone hole patterns. Also, to conserve instrumentation ring thermocouples, the maximum temperature of an individual exhaust thermocouple was kept below 2200°F. The liner individual outlet temperatures are shown in Figures 156 through 160 for approximately 75%-power conditions for each of the liner configurations. The annulus heights are not to scale since the diameters of the annulus hub and tip are 5.14 inches and 6.12 inches, respectively, so that the height is approximately .50 inch. A summary of the two temperature-pattern quality parameters is given in Table 88 for each liner configuration and the approximate power levels where they were tested. The final liner configuration used for the emissions testing was prechamber liner No. 17. The pattern factor values in Table 88 used baseline engine values for the combustor inlet temperature, T_3 since the low-emission liners measured this temperature with a thermocouple through the outer case dome.

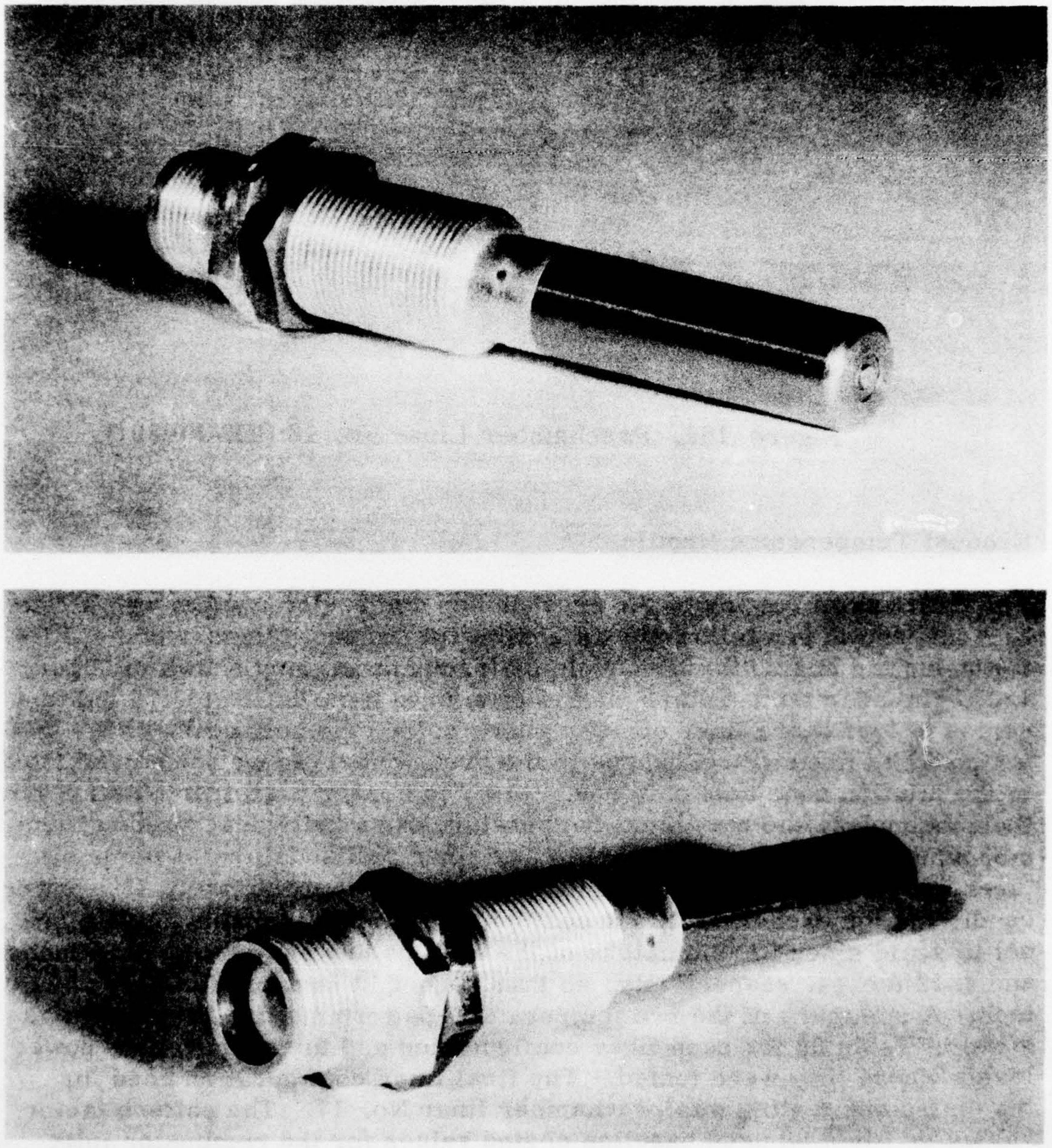


Figure 152. Prechamber Spark Igniter, EX-115299.

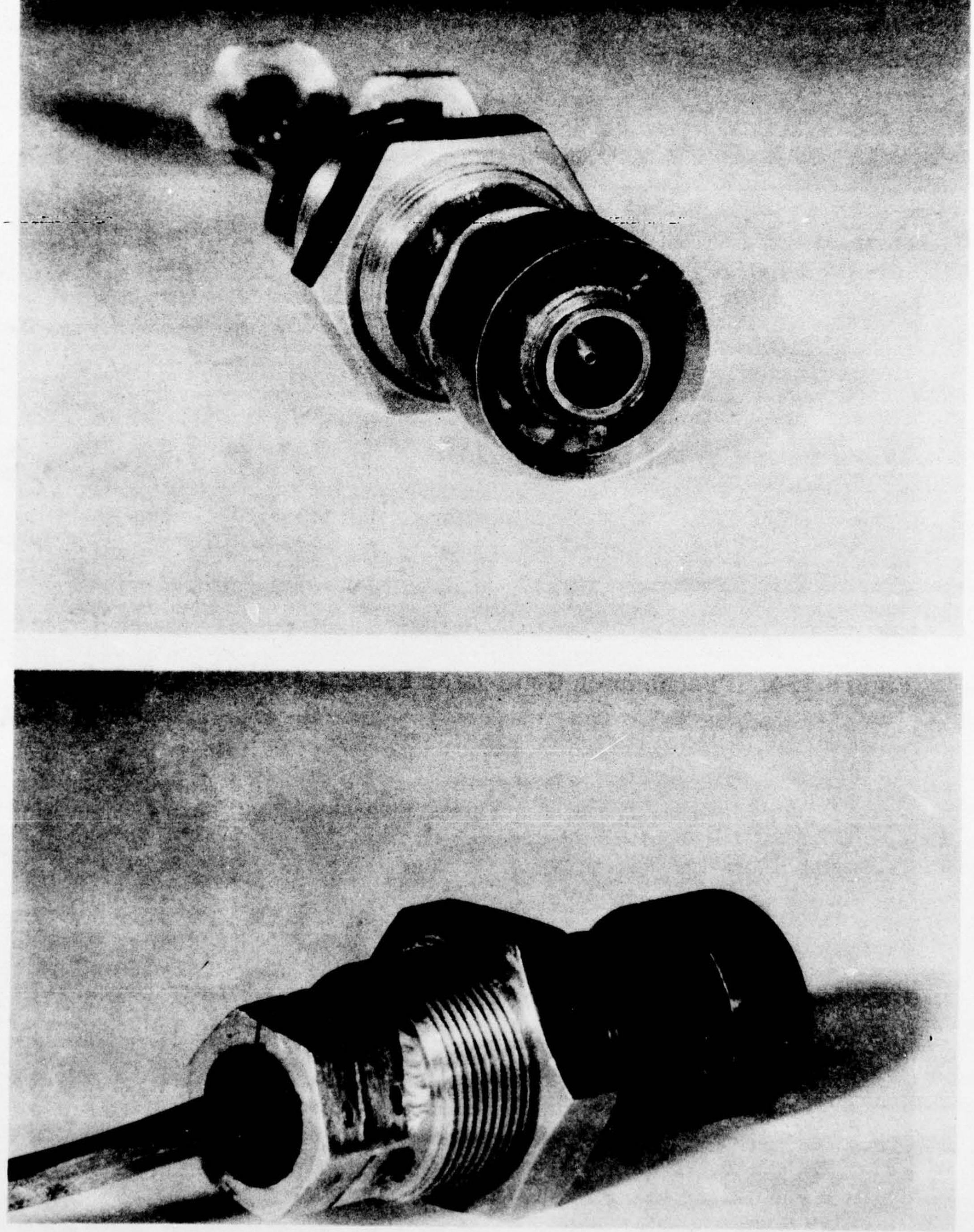


Figure 153. Prechamber Airblast Fuel Nozzle, EX-115870.

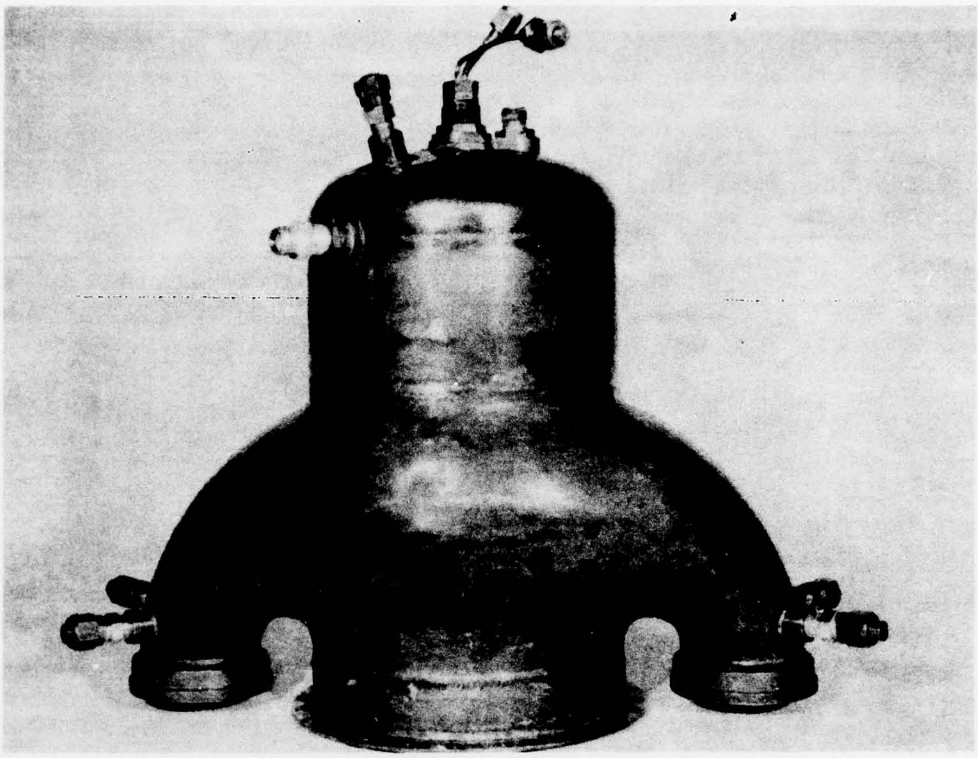


Figure 154. Prechamber Combustor System Assembly, External View.

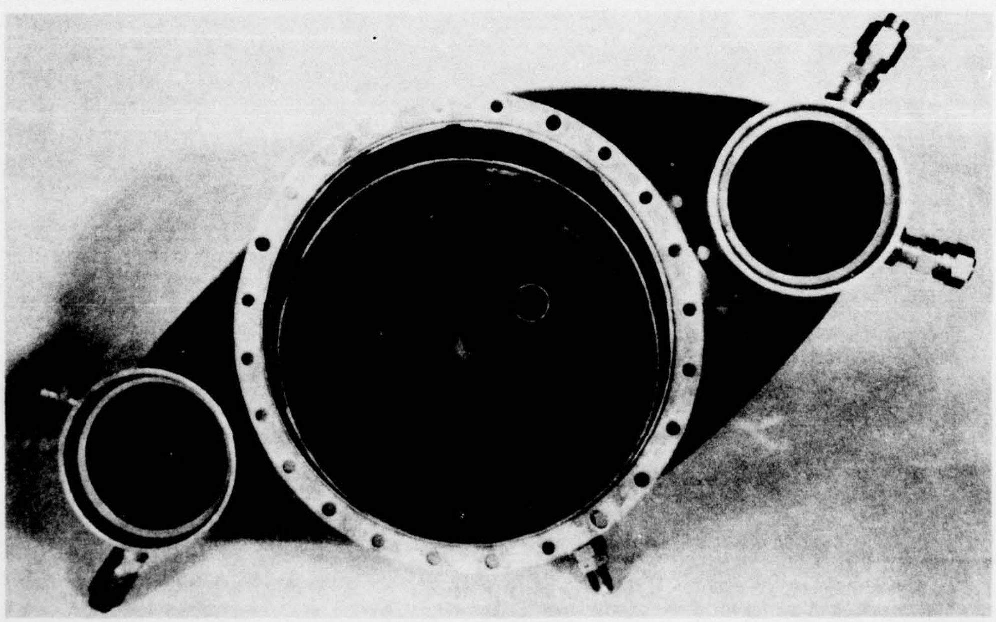


Figure 155. Prechamber Combustor System Assembly, Internal View.

LOW-EMISSION PRECHAMBER COMBUSTOR SYSTEM OPERATING AT 75% POWER TURBINE TEMP
TEST DATE = 3-26-75 READING NUMBER = 212 INLET TEMP = 518.
ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 1325.
OUTER CASE NUMBER/NAME = EX-114012 / EXTENDED LENGTH
LINER NUMBER/NAME = EX-116291 / PRECHAMBER

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1774.7	1780.0	1803.3	1785.9
MAXIMUM TEMPERATURE	2020.0	2250.0	2210.0	2250.0
(AVG-INLET) TEMP	1256.7	1262.0	1285.3	1267.9
(MAX-AVG) TEMP	245.3	470.0	406.7	464.1
MAX TEMP/AVG TEMP	1.1382	1.2640	1.2255	1.2599
(MAX-AVG)/(AVG-IN)	0.1952	0.3724	0.3164	0.3661
(AVG-AVG TOTAL)	-11.2	-5.9	17.4	
(TIP-HUB) AVG TEMP				28.6
(AVG TOTAL-TOT)				460.9

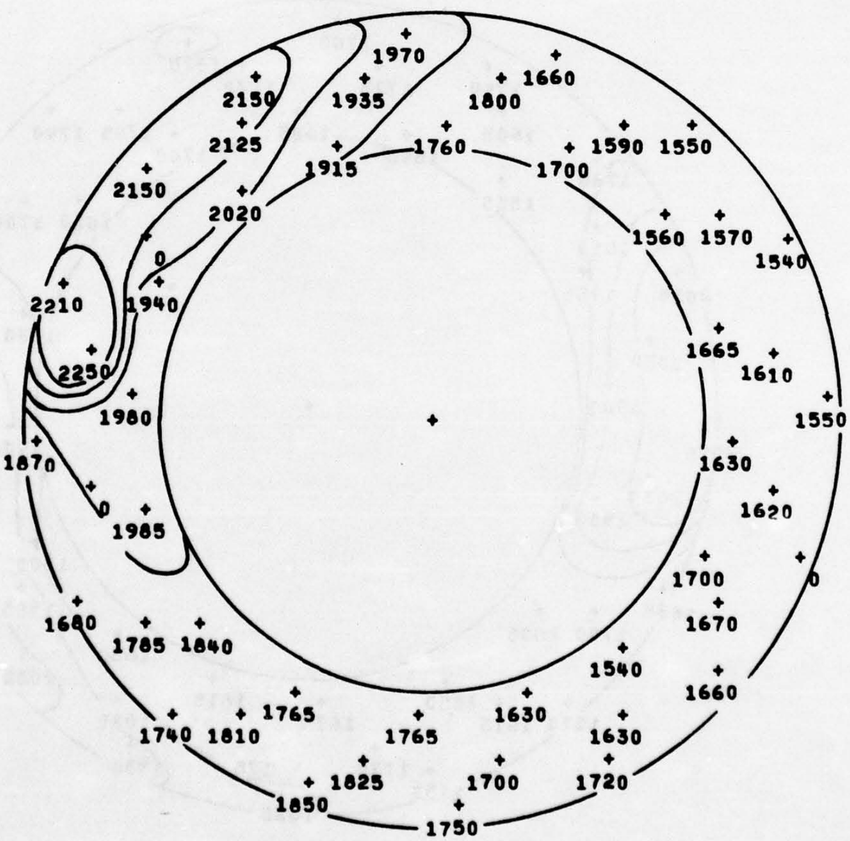
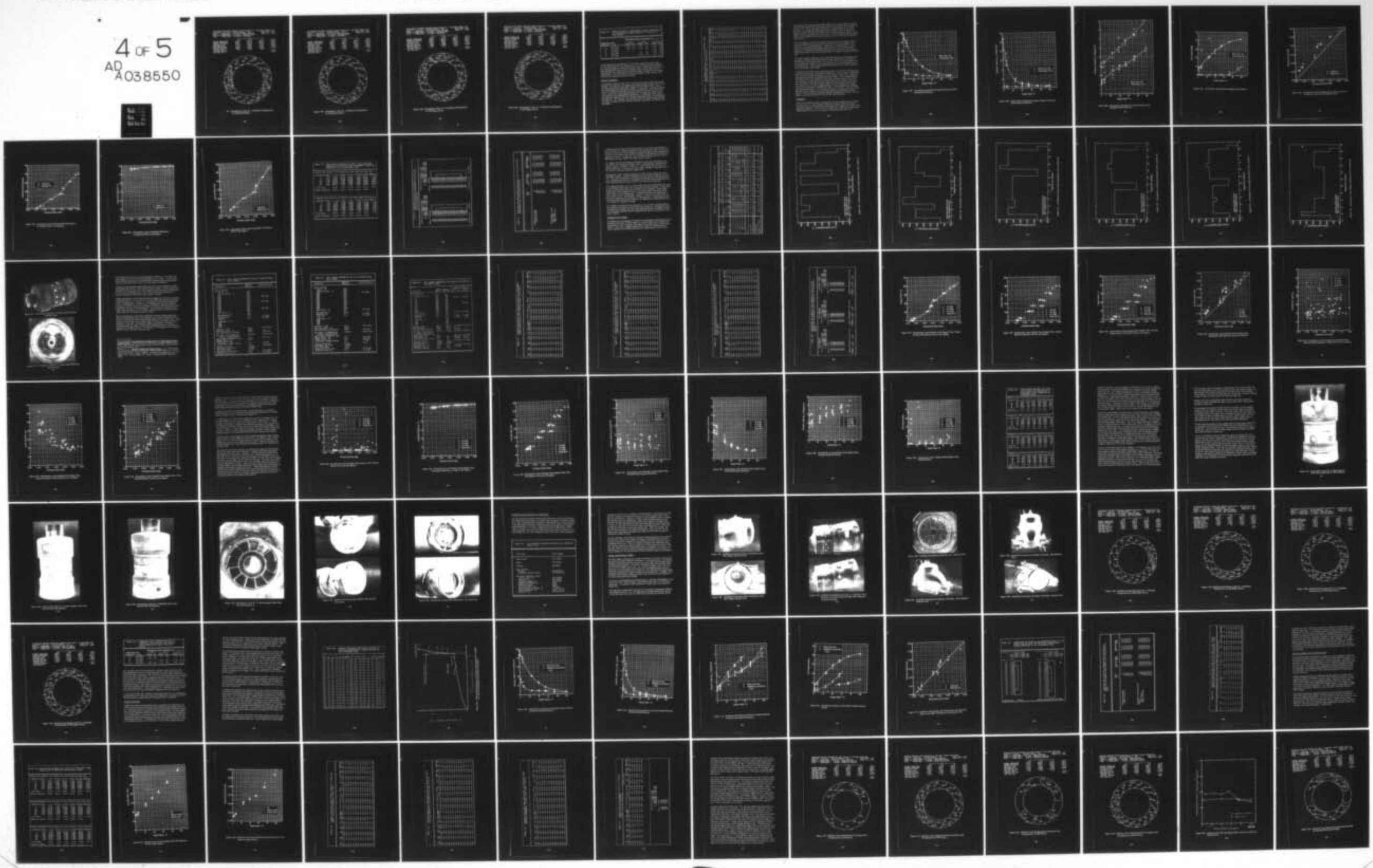


Figure 156. Prechamber Liner No. 13 Exhaust Temperatures at 75% Engine Power.

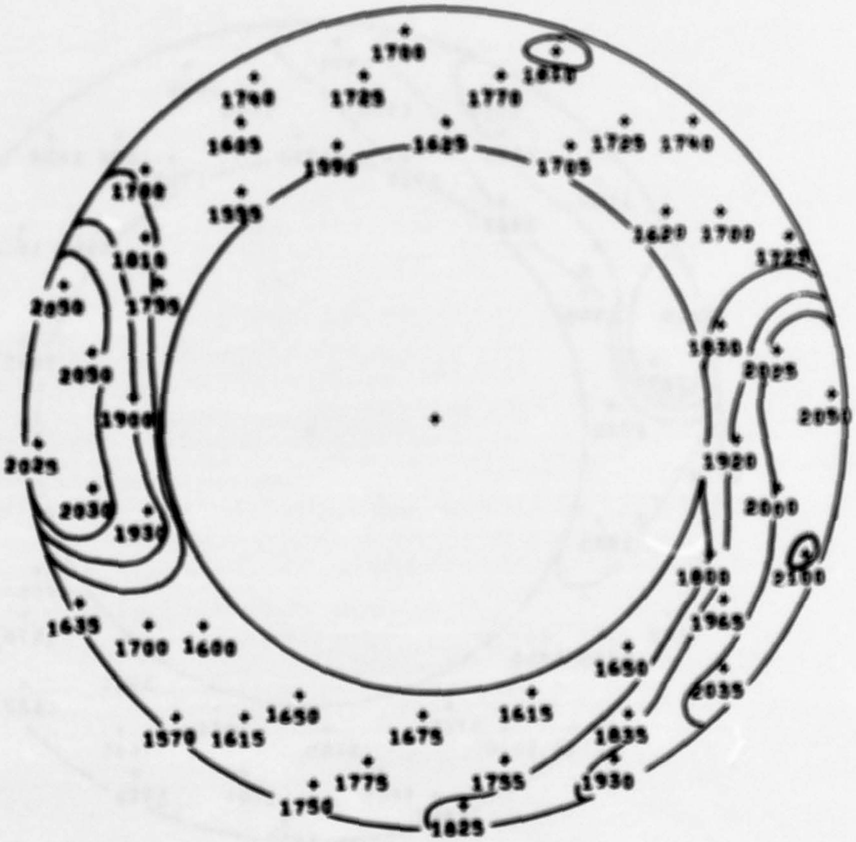
AD-A038 550 GENERAL MOTORS CORP INDIANAPOLIS IND DETROIT DIESEL --ETC F/G 21/5
LOW-EMISSIONS COMBUSTOR DEMONSTRATION.(U)
MAR 77 D L TROTH DAAJ02-74-C-0025
UNCLASSIFIED DDA-EDR-8723 USAAMRDL-TR-76-29 NL

4 OF 5
AD A038550



LOW-EMISSION PRECHAMBER COMBUSTOR SYSTEM OPERATING AT 75% POWER TURBINE TEMP
TEST DATE = 4- 1-75 READING NUMBER = 216 INLET TEMP = 516.
ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 1320.
OUTER CASE NUMBER/NAME = EX-119012 / EXTENDED LENGTH
LINER NUMBER/NAME = EX-119064 / PRECHAMBER

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1713.7	1817.0	1841.6	1791.0
MAXIMUM TEMPERATURE	1930.0	2050.0	2100.0	2100.0
(AVG-INLET) TEMP	1197.7	1301.0	1325.6	1275.0
(MAX-AVG) TEMP	216.2	232.2	258.4	309.0
MAX TEMP/AVG TEMP	1.1262	1.1277	1.1403	1.1725
(MAX-AVG)/(AVG-IN)	0.1805	0.1784	0.1950	0.2423
(AVG-AVG TOTAL)	-77.3	26.0	50.5	
(TIP-HUB) AVG TEMP				127.8
(AVG TOTAL-TOT)				471.0



157. Prechamber Liner No. 14 Exhaust Temperatures at 75% Engine Power.

```
LOW-EMISSION PRECHAMBER COMBUSTOR SYSTEM OPERATING AT  75% POWER TURBINE TEMP
TEST DATE =  4- 3-75      READING NUMBER =   229                 INLET TEMP =  500.
ENGINE      NUMBER/NAME = CAE 821233 / MODEL 250-C20B           ENGINE TOT = 1270.
OUTER CASE NUMBER/NAME =  EX-114012 / EXTENDED LENGTH
LINER       NUMBER/NAME =  EX-119065 / PRECHAMBER
```

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1717.1	1733.7	1724.0	1725.1
MAXIMUM TEMPERATURE	2060.0	2110.0	2060.0	2110.0
(AVG-INLET) TEMP	1217.1	1233.7	1224.0	1225.1
(MAX-AVG) TEMP	342.9	376.3	336.0	384.9
MAX TEMP/AVG TEMP	1.1997	1.2171	1.1949	1.2231
(MAX-AVG)/(AVG-IN)	0.2817	0.3051	0.2745	0.3142
(AVG-AVG TOTAL)	-8.0	8.6	-1.1	
(TIP-HUB) AVG TEMP				6.9
(AVG TOTAL-TOT)				455.1

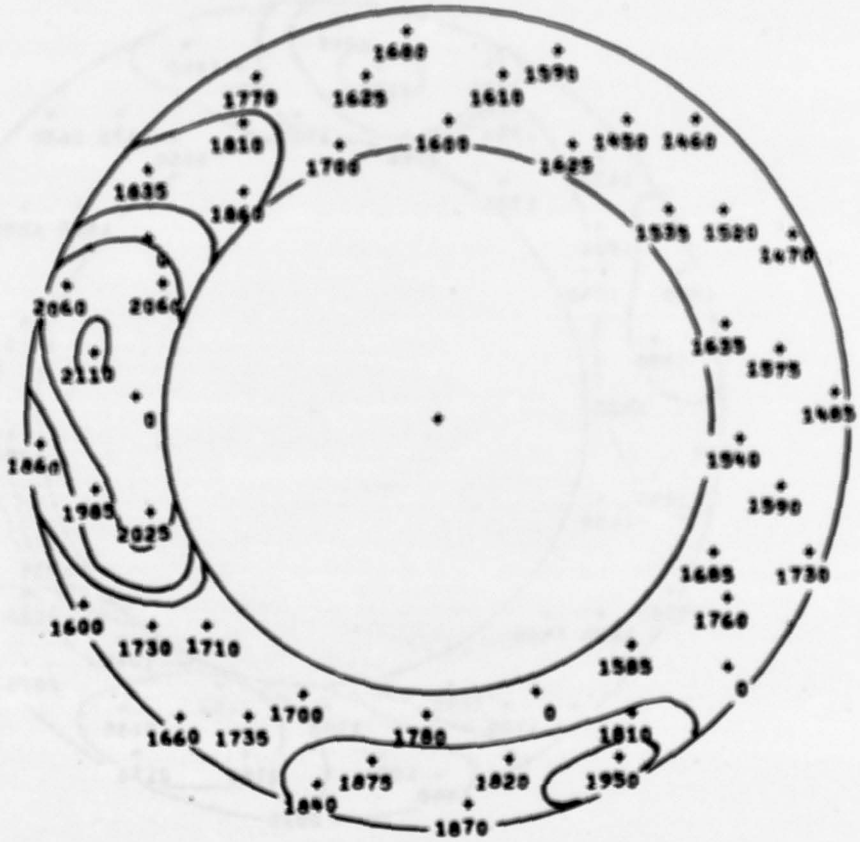


Figure 158. Prechamber Liner No. 15 Exhaust Temperatures at 75% Engine Power.

```
LOW-EMISSION PRECHAMBER COMBUSTOR SYSTEM OPERATING AT  75% POWER TURBINE TEMP
TEST DATE =  4- 7-75     READING NUMBER =   229                 INLET TEMP =  512.
ENGINE      NUMBER/NAME = CAE 821233 / MODEL 250-C28B           ENGINE TOT = 1305.
OUTER CASE NUMBER/NAME =  EX-119812 / EXTENDED LENGTH
LINER       NUMBER/NAME =  EX-119886 / PRECHAMBER
```

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1782.2	1874.1	1884.4	1846.9
MAXIMUM TEMPERATURE	2150.0	2160.0	2130.0	2160.0
(AVG-INLET) TEMP	1270.2	1362.1	1372.4	1334.9
(MAX-AVG) TEMP	367.8	285.9	245.6	313.1
MAX TEMP/AVG TEMP	1.2064	1.1526	1.1303	1.1695
(MAX-AVG)/(AVG-IN)	0.2896	0.2099	0.1790	0.2346
(AVG-AVG TOTAL)	-64.7	27.2	37.5	
(TIP-HUB) AVG TEMP				102.2
(AVG TOTAL-TOT)				541.9

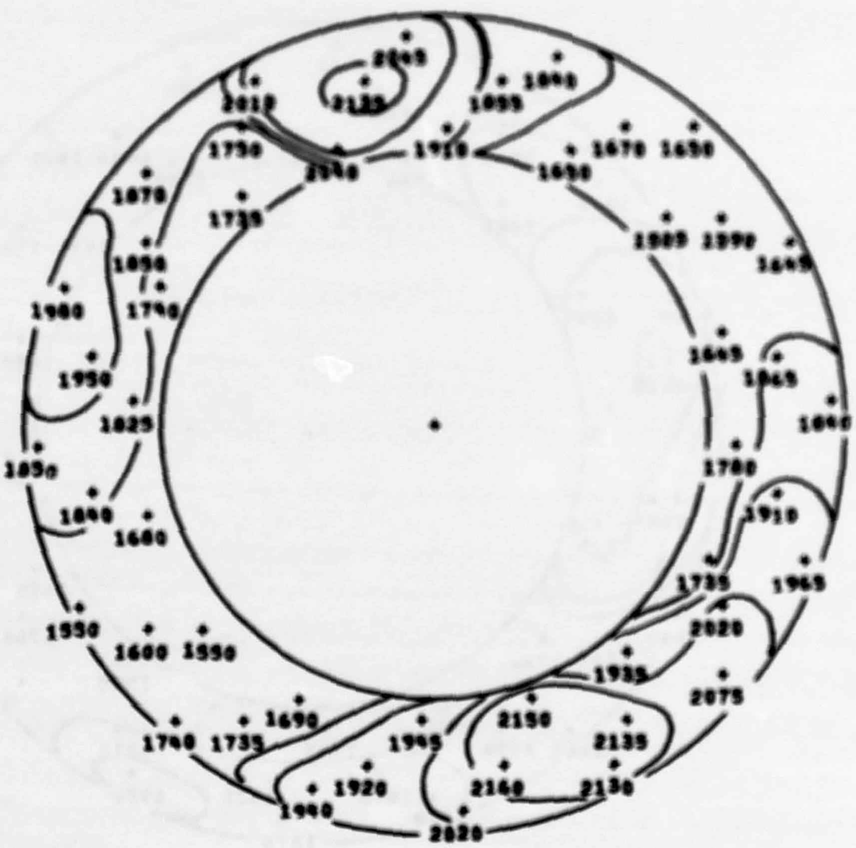


Figure 159. Prechamber Liner No. 16 Exhaust Temperatures at 75% Engine Power.

```
LOW-EMISSION PRECHAMBER COMBUSTOR SYSTEM OPERATING AT  75% POWER TURBINE TEMP
TEST DATE =  4-11-75      READING NUMBER =    288                    INLET TEMP =  516.
ENGINE       NUMBER/NAME = CAE 821253 / MODEL 250-C20B               ENGINE TOT = 1320.
OUTER CASE NUMBER/NAME =  EX-119012 / EXTENDED LENGTH
LINER        NUMBER/NAME =  EX-119087 / PRECHAMBER
```

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1750.6	1872.2	1913.4	1845.4
MAXIMUM TEMPERATURE	1920.0	2060.0	2180.0	2180.0
(AVG-INLET) TEMP	1234.6	1356.2	1397.4	1329.4
(MAX-AVG) TEMP	169.4	187.8	266.6	334.6
MAX TEMP/AVG TEMP	1.0968	1.1003	1.1393	1.1813
(MAX-AVG)/(AVG-IN)	0.1372	0.1385	0.1908	0.2517
(AVG-AVG TOTAL)	-94.8	26.8	68.0	
(TIP-HUB) AVG TEMP				162.8
(AVG TOTAL-TOT)				525.4

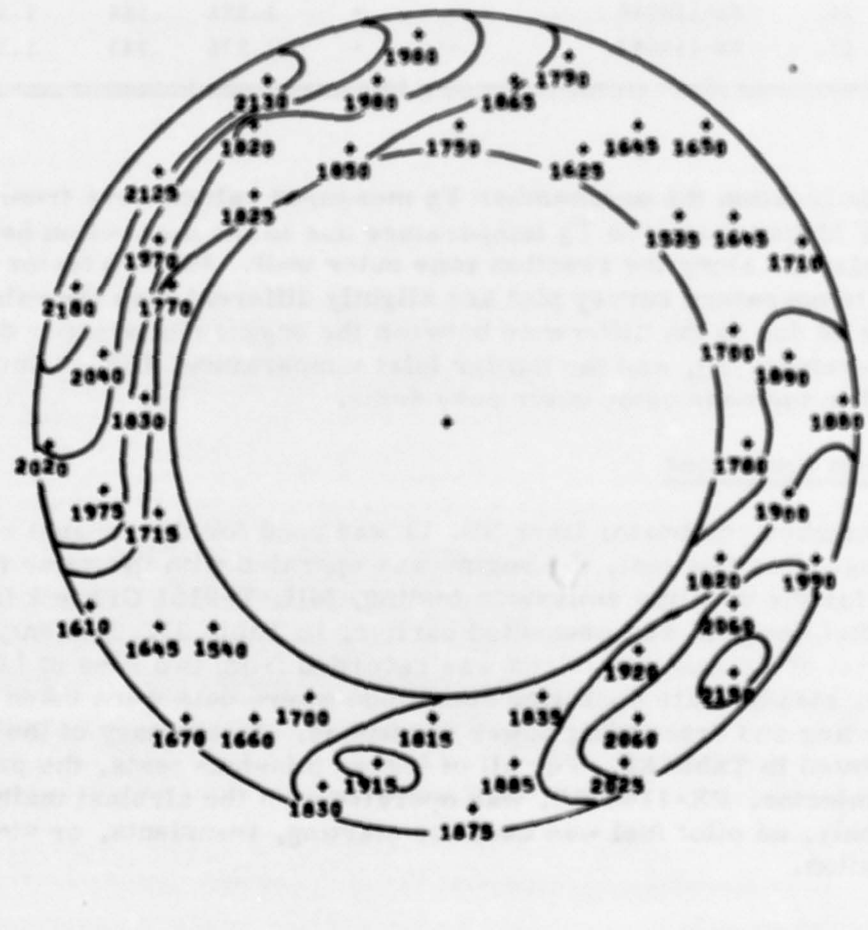


Figure 160. Prechamber Liner No. 17 Exhaust Temperatures at 75% Engine Power.

TABLE 88. COMBUSTOR OUTLET TEMPERATURE PROFILE PARAMETERS FOR PRECHAMBER LINERS OPERATING IN MODEL 250-C20B ENGINE

Combustion Liner		Approximate Output Horsepower (%)					
		40		55		75	
Series No.	P/N	Tm/Ta	P.F.	Tm/Ta	P.F.	Tm/Ta	P.F.
13.	EX-116291	1.266	.375	1.224	.317	1.260	.366
14.	EX-119064	1.167	.232	1.176	.247	1.172	.242
15.	EX-119065	-	-	-	-	1.223	.314
16.	EX-119086	-	-	1.191	.264	1.169	.234
17.	EX-119087	-	-	1.176	.243	1.181	.252

At this location the prechamber T_3 measured values were from 50 to 150°F higher than true T_3 temperature due to the convection heating of the inlet air along the reaction zone outer wall. Pattern factor values on each temperature survey plot are slightly different than the values in Table 88 due to the difference between the engine compressor discharge temperature, T_3, and the burner inlet temperature, BIT, values measured in the combustor outer case dome.

Exhaust Emissions

Prechamber combustor liner No. 17 was used for the exhaust emissions testing. For this test, the engine was operated with the same fuel as was used for the baseline emissions testing, MIL-T-5161 Grade 1 (JP-4). The fuel analysis was presented earlier, in Table 83. A twenty-six point data set of exhaust emissions was recorded from two runs of LOH duty cycle, steady-state operating conditions where data were taken in both ascending and descending power sequences. A summary of the data is presented in Table 89. For all of these emissions tests, the prechamber fuel injector, EX-115870C, was operated with the airblast main fuel system only, no pilot fuel was used for starting, transients, or steady state operation.

TABLE 89. PRECHAMBER LINER NO. 17, JP-4 REFERENCE FUEL, INITIAL ENGINE TEST SERIES DATA

ROG NO	NOX PPM	CO PPM	CH4 PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CH4	NOX	HORSEPOWER HP	PC
289.	23.1	248.0	17.0	2.48	68.3	37.0	0.01232	0.01100	1.120	99.461	19.696	0.773	3.013	5.0	1.2
290.	27.0	194.0	21.0	2.64	78.6	29.0	0.01310	0.01160	1.129	99.569	14.510	0.899	3.317	30.6	7.3
291.	38.0	145.0	22.0	3.08	116.5	42.5	0.01527	0.01460	1.046	99.694	9.321	0.810	4.212	106.6	25.4
292.	78.0	106.0	22.5	3.58	143.5	1.0	0.01776	0.01530	1.161	99.769	5.873	0.714	7.098	167.8	39.9
293.	75.5	91.0	19.5	3.68	169.4	1.0	0.01826	0.01600	1.141	99.803	4.908	0.602	6.688	230.2	54.8
294.	98.0	81.0	25.5	4.00	211.1	1.0	0.01987	0.01840	1.080	99.807	4.020	0.725	7.989	311.2	74.3
295.	122.0	83.0	26.0	4.45	253.1	7.0	0.02215	0.02080	1.065	99.825	3.704	0.664	8.942	397.3	94.6
296.	91.5	82.5	24.5	4.00	211.1	1.0	0.01987	0.01840	1.080	99.811	4.095	0.636	7.459	307.3	73.2
297.	77.0	95.0	22.5	3.64	172.4	1.0	0.01826	0.01620	1.127	99.789	5.123	0.695	6.820	229.2	54.6
298.	62.0	113.0	18.5	3.53	142.5	1.0	0.01751	0.01520	1.152	99.775	6.369	0.595	5.721	165.4	39.3
299.	51.6	128.0	21.0	3.06	116.0	1.0	0.01536	0.01460	1.058	99.715	8.286	0.778	5.487	105.0	25.0
300.	35.0	153.0	18.5	2.60	77.5	1.0	0.01288	0.01160	1.110	99.629	11.627	0.806	4.373	29.0	6.9
301.	29.5	164.0	21.0	2.49	65.9	1.0	0.01273	0.01070	1.159	99.597	13.016	0.956	3.845	6.5	1.5
302.	33.0	157.0	20.5	2.46	67.3	1.0	0.01258	0.01100	1.107	99.605	12.613	0.963	4.355	5.7	1.4
303.	37.0	150.0	14.0	2.64	76.5	1.0	0.01307	0.01140	1.147	99.666	11.263	0.603	4.584	29.0	6.9
304.	53.0	125.0	17.5	3.18	117.0	1.0	0.01576	0.01460	1.079	99.760	7.790	0.625	5.425	108.0	25.8
305.	67.0	113.0	21.5	3.61	143.0	1.0	0.01792	0.01530	1.171	99.769	6.208	0.676	6.046	169.0	40.2
306.	76.0	94.5	29.0	3.69	169.9	1.0	0.01821	0.01600	1.149	99.773	5.085	0.893	6.712	229.4	54.6
307.	91.0	86.0	37.5	4.03	211.5	1.0	0.02003	0.01850	1.083	99.776	4.235	1.057	7.960	311.0	74.0
308.	103.0	86.5	19.0	4.20	251.3	9.0	0.02128	0.02050	1.038	99.827	4.019	0.505	7.849	389.0	92.6
309.	90.5	84.5	35.0	4.05	210.1	4.0	0.02013	0.01840	1.094	99.788	4.349	0.982	7.285	306.3	72.9
310.	73.0	98.0	23.0	3.76	171.4	1.0	0.01866	0.01620	1.152	99.790	5.172	0.695	6.528	226.1	53.8
311.	62.5	118.0	22.5	3.49	144.5	1.0	0.01832	0.01550	1.182	99.767	6.342	0.692	5.557	167.8	39.9
312.	48.0	125.0	24.5	3.18	116.5	1.0	0.01576	0.01460	1.080	99.720	7.788	0.874	4.912	105.0	25.0
313.	33.5	160.0	25.0	2.78	77.7	1.0	0.01378	0.01180	1.168	99.629	11.985	1.028	3.924	28.3	6.7
314.	29.5	164.0	17.0	2.48	66.8	1.0	0.01228	0.01090	1.127	99.611	13.068	0.776	3.865	5.0	1.2

Emission index versus percent output power plots comparing prechamber and baseline combustor performance are given in Figures 161 through 163 for CO, CH_x, NO_x, and Figure 164 shows comparison plots for smoke number. A comparison of chemical and mechanical fuel-air ratios is given in Figure 165 and shows that the chemically computed values were higher than the mechanical in every case. The mechanical fuel-air ratios from the prechamber were nearly identical to the values for the baseline liner tested.

The horsepower versus chemical fuel-air ratio curve in Figure 166 was used to establish the proper fuel-air ratio levels to correspond to the LOH duty cycle operating points. Using these chemical fuel-air ratios, exhaust concentrations and engine fuel rates for each LOH duty cycle point were obtained and pollutant emission index values were computed. Combustion efficiencies and fuel flow rates are plotted in Figures 167 and 168.

The time-weighted LOH duty cycle emissions from the prechamber liner are given in Table 90 and show that the total emissions were reduced 51.1% below the baseline level. The levels of CO, CH_x, and smoke were all significantly reduced, but NO_x emissions increased 52% above baseline NO_x levels. This is approximately the same NO_x average observed in the combustor rig testing.

An analysis was made of the comparison ratio of chemical to mechanical fuel-air ratios for the prechamber combustor. These results, along with those for the baseline combustor, are presented in Table 91. Table 92 summarizes all of the mechanical fuel-air ratios. The mechanical fuel-air ratios were very consistent from point to point on each liner and between liners. Chemical fuel-air ratios varied more widely. The numbers in Table 91 give the average chemical-to-mechanical ratio of fuel-air ratios, the 1, 2, and 3 sigma ranges, and their rank in ascending order of the chemical to mechanical ratios. The baseline liner average agreement was within +1.1%, but the prechamber produced chemical fuel-air ratios 10.9% higher on the average than the mechanically derived values. Other than some inherent exhaust distribution problems with this liner, no reason was found for these high concentrations.

Durability

After the emissions testing, a durability test was conducted on prechamber liner No. 17. This testing consisted of twenty 2:06 hour periods. Each 2:06 hour period allowed the operation of the engine over each of six durability profiles. Each set of six profiles was followed by engine shutdown periods of three or ten minutes, alternating with each set.

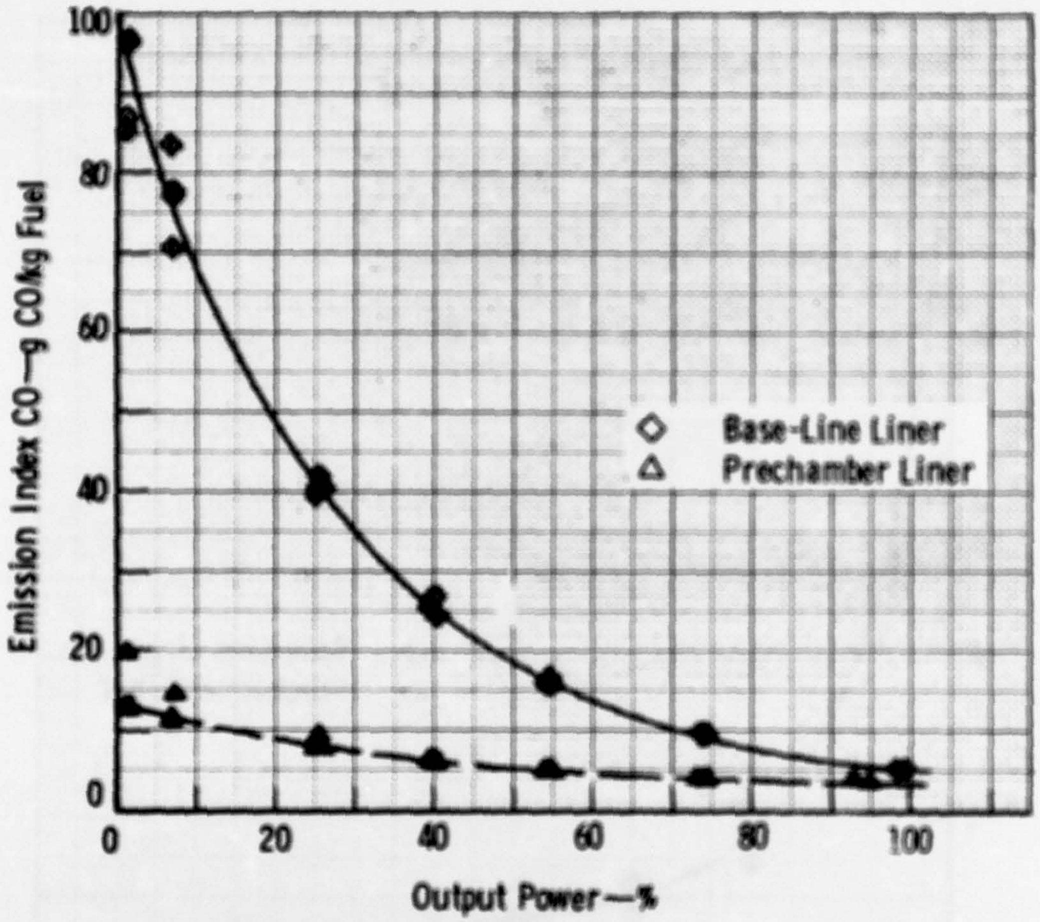


Figure 161. Prechamber and Baseline Engine Exhaust Carbon Monoxide Emissions.

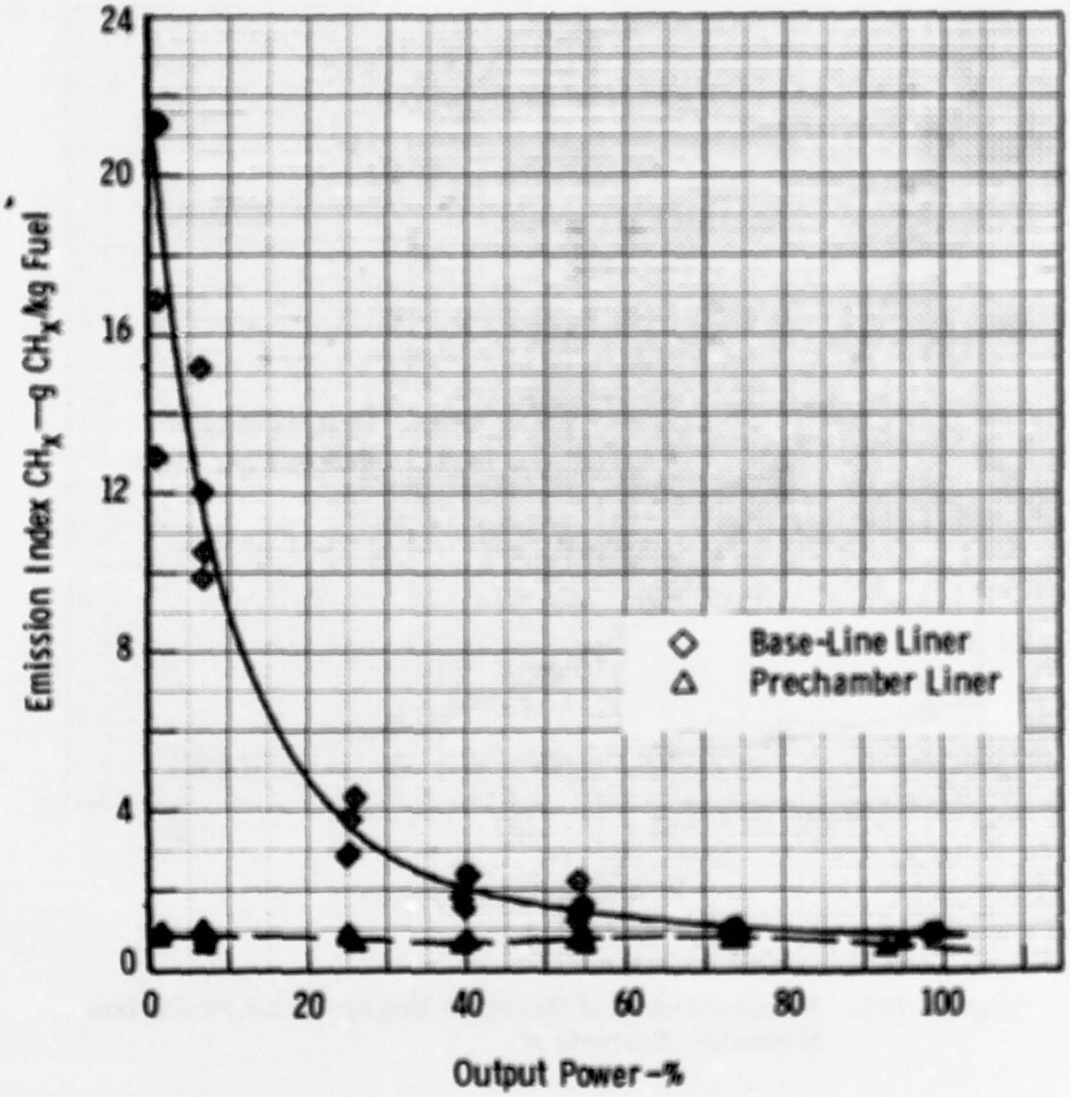


Figure 162. Prechamber and Baseline Engine Exhaust Unburned Hydrocarbon Emissions.

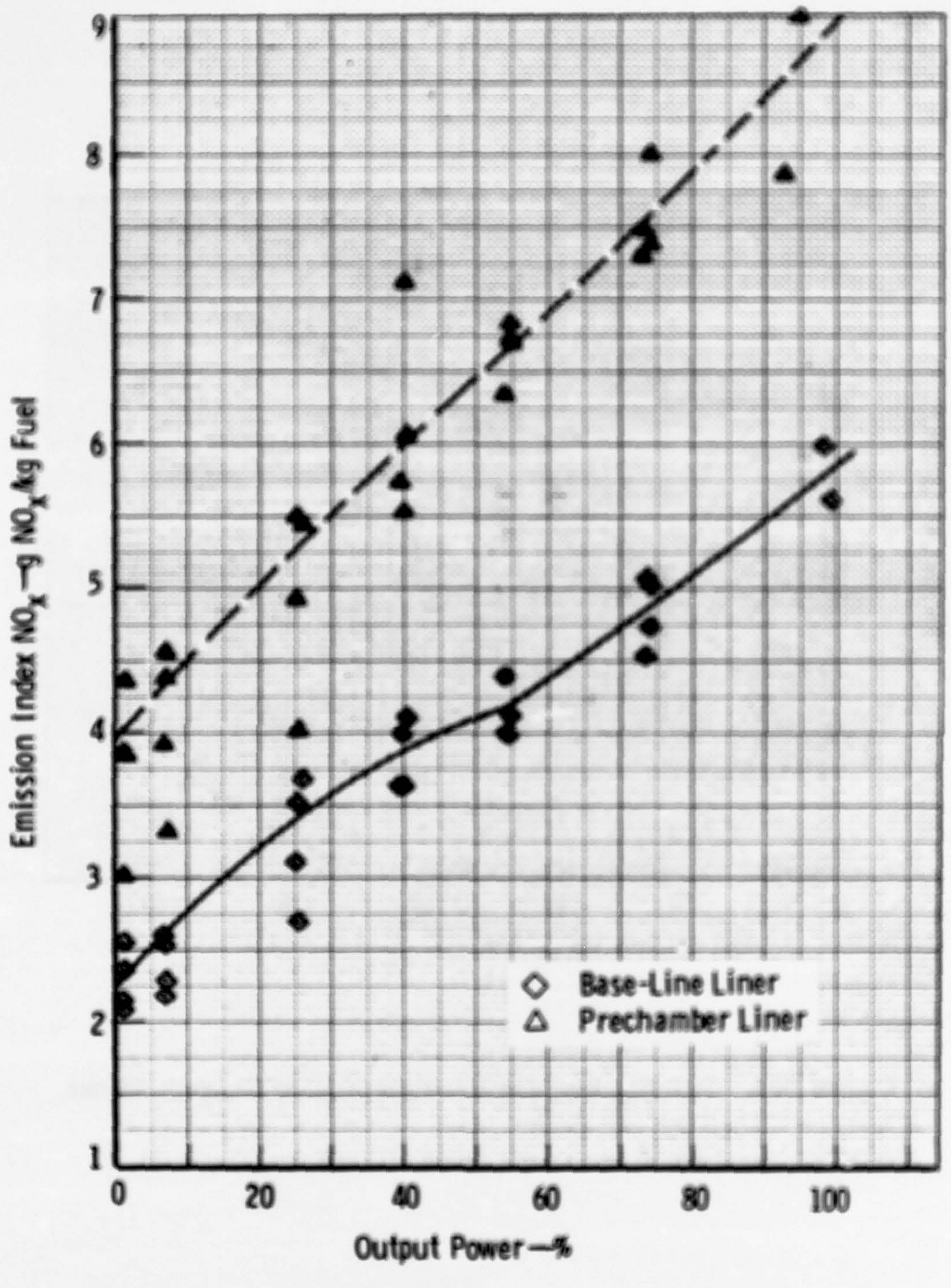


Figure 163. Prechamber and Baseline Engine Exhaust Total Nitrogen Oxide Emissions.

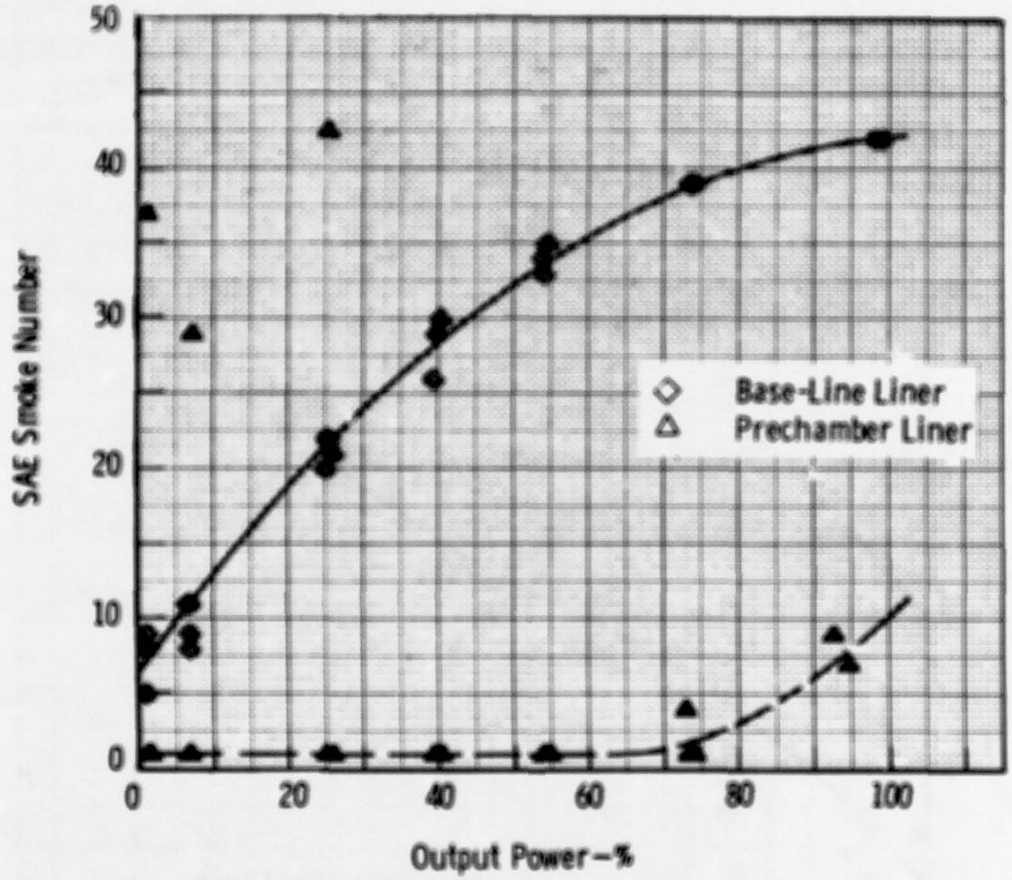


Figure 164. Prechamber and Baseline Engine Exhaust Smoke.

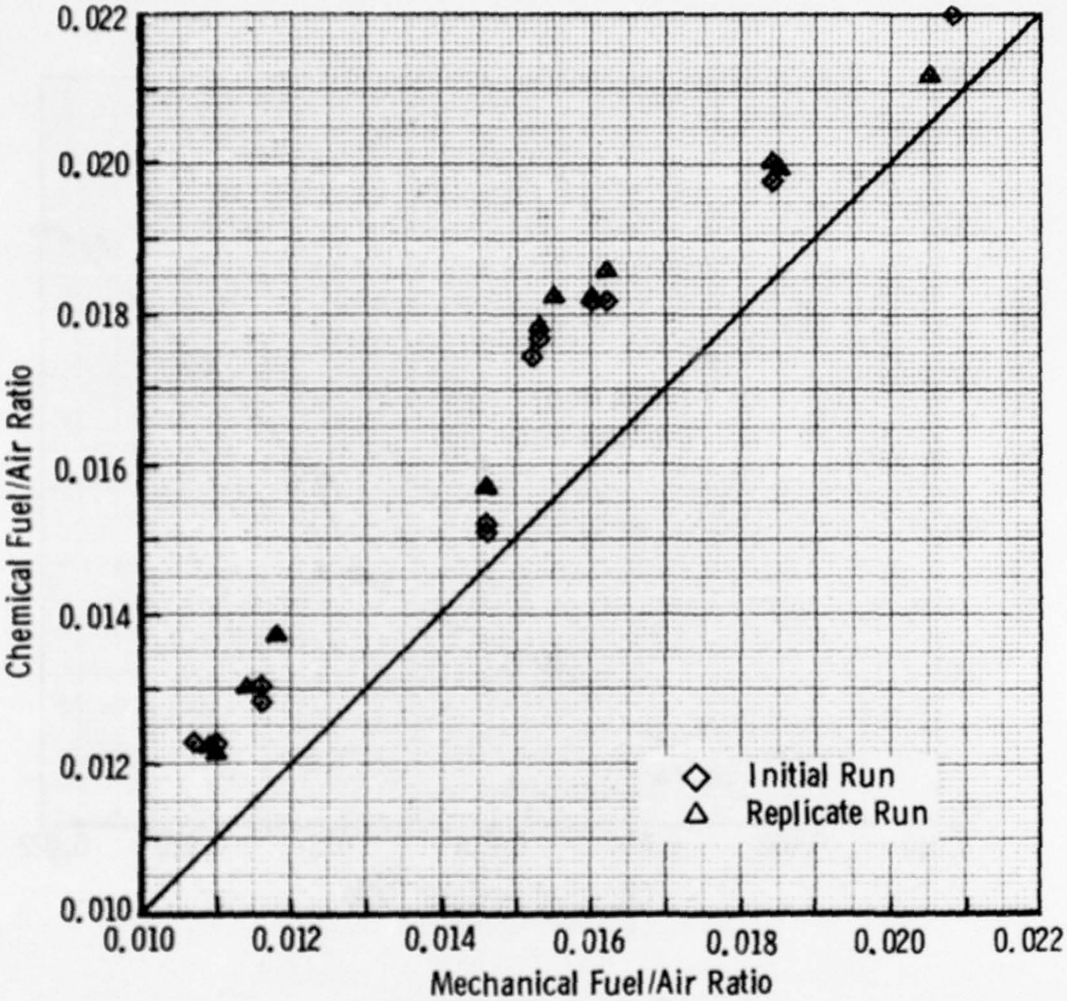


Figure 165. Prechamber Liner Mechanical and Chemical Fuel to Air Ratio Comparison from Engine Test.

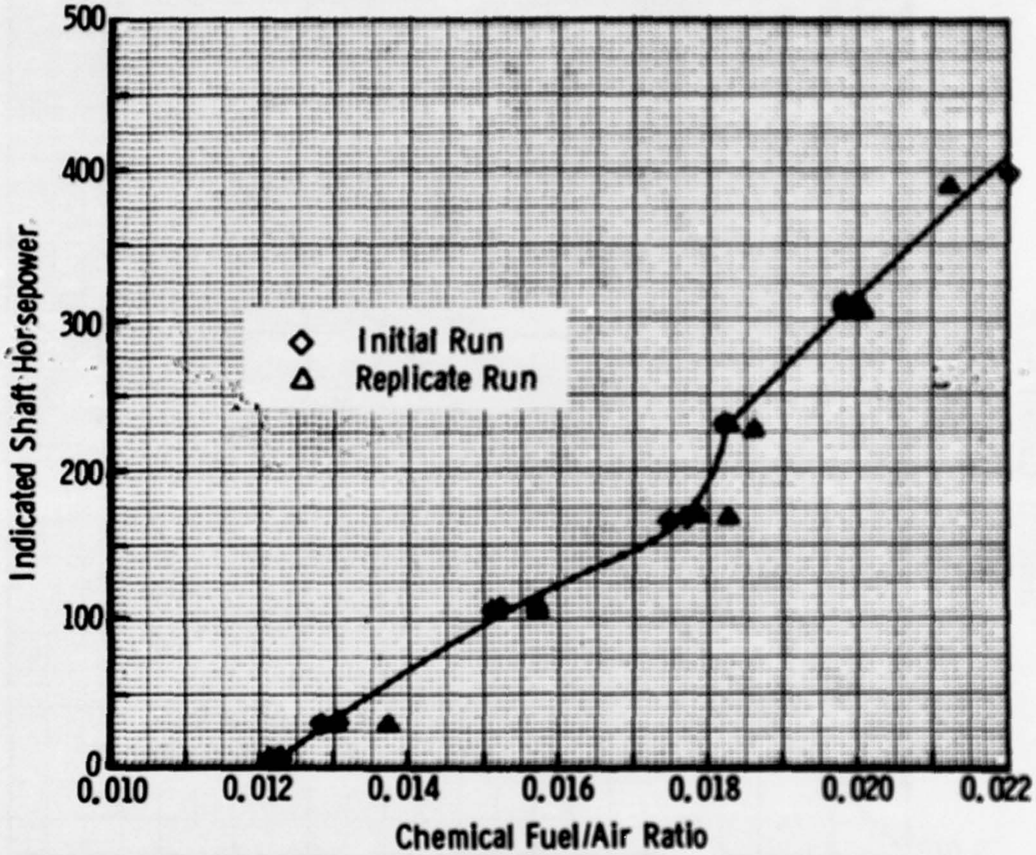


Figure 166. Prechamber Liner Indicated Shaft Horsepower at Chemical Fuel-to-Air Ratios.

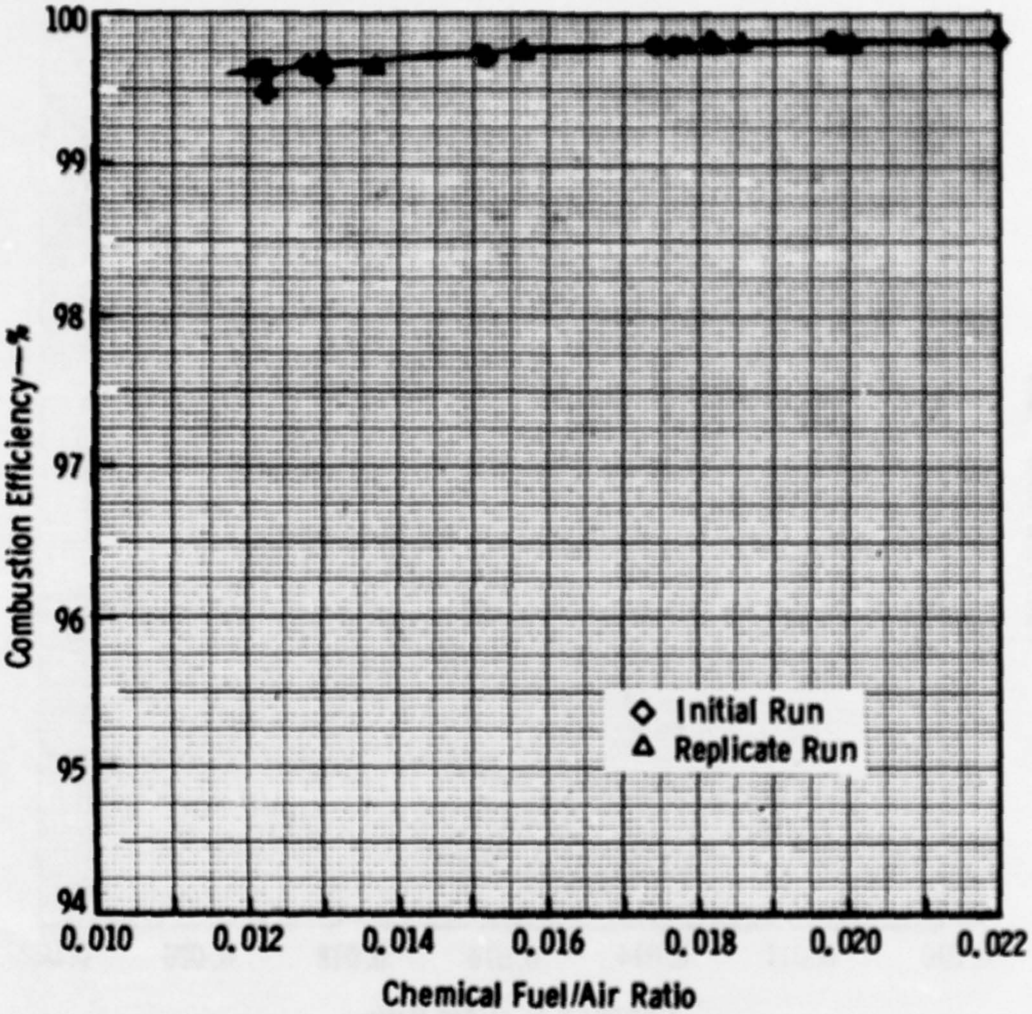


Figure 167. Prechamber Liner Combustion Efficiency at Chemical Fuel-to-Air Ratios.

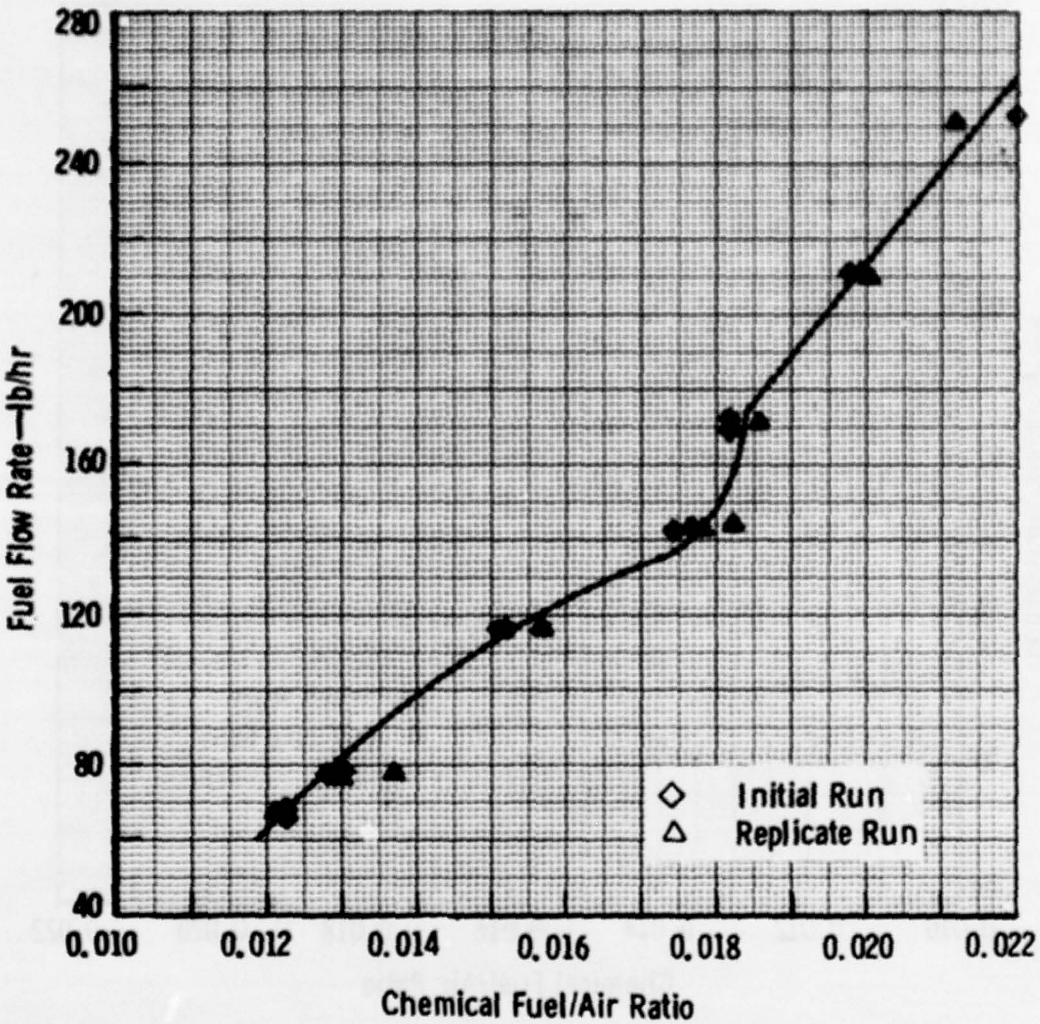


Figure 168. Prechamber Liner Fuel Flow Rates at Chemical Fuel-to-Air Ratios.

TABLE 90. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS COMPARISON OF BASELINE AND PRECHAMBER COMBUSTORS OPERATING ON JP-4 REFERENCE FUEL.

BASELINE LINER, 6871486, JP-4 REFERENCE FUEL, APRIL ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	70.00	17.354	92.163	2.250	111.767	6.80
6.	0.15	78.00	12.110	78.205	2.359	92.674	9.80
25.	0.00	116.00	3.535	41.387	2.996	47.918	20.50
40.	0.15	143.00	1.959	24.852	3.605	30.416	28.40
55.	0.45	170.00	1.411	17.058	4.514	22.983	34.50
75.	0.20	209.00	1.008	9.337	4.952	15.297	39.20
100.	0.05	262.00	1.080	5.522	5.782	12.384	42.10
CYCLE TOTALS		164.55	2.114	19.542	4.454	26.111	42.10
PERCENT OF BASELINE		100.00	100.00	100.00	100.00	100.00	

PRECHAMBER LINER, EX-119087, JP-4 REFERENCE FUEL, APRIL ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	67.00	0.909	12.699	3.976	17.584	1.00
6.	0.15	76.00	0.879	11.909	4.376	17.164	1.00
25.	0.00	116.00	0.754	8.480	5.364	14.598	1.00
40.	0.15	144.00	0.685	6.170	5.827	12.682	1.00
55.	0.45	172.00	0.684	5.001	6.683	12.368	1.00
75.	0.20	213.00	0.683	4.138	7.606	12.427	3.30
100.	0.05	268.00	0.670	3.751	8.226	12.647	10.20
CYCLE TOTALS		166.40	0.696	5.304	6.774	12.775	10.20
PERCENT OF BASELINE		101.12	32.92	27.14	152.08	48.93	

TABLE 91. COMPARISON OF CHEMICAL AND MECHANICAL FUEL-TO-AIR RATIOS FOR BASELINE AND PRECHAMBER LINERS OPERATING ON JP-4 REFERENCE FUEL

Baseline Liner 6871486

RATIO OF F/A C/M AVG = 1.016
SIGMA = 0.036
1 SIGMA RANGE = 0.981 1.052
2 SIGMA RANGE = 0.945 1.088
3 SIGMA RANGE = 0.909 1.124

RDG NO	FAC/FAM
242	0.9452
254	0.9576
234	0.9606
247	0.9746
241	0.9834
255	0.9835
248	0.9849
235	0.9971
237	1.0028
239	1.0029
243	1.0050
238	1.0121
244	1.0202
251	1.0244
240	1.0246
245	1.0303
252	1.0370
249	1.0377
250	1.0395
253	1.0475
233	1.0483
246	1.0508
236	1.0569
232	1.0577
257	1.0720
256	1.0721

Prechamber Liner EX-119087

RATIO OF F/A C/M AVG = 1.114
SIGMA = 0.043
1 SIGMA RANGE = 1.072 1.157
2 SIGMA RANGE = 1.029 1.200
3 SIGMA RANGE = 0.987 1.242

RDG NO	FAC/FAM
308	1.0382
299	1.0385
291	1.0460
295	1.0648
304	1.0794
312	1.0797
294	1.0798
296	1.0798
307	1.0826
309	1.0939
302	1.1074
300	1.1100
289	1.1204
314	1.1269
297	1.1271
290	1.1290
293	1.1410
306	1.1445
303	1.1466
298	1.1521
310	1.1521
301	1.1528
292	1.1609
313	1.1678
305	1.1709
311	1.1820

TABLE 92. BASELINE AND PRECHAMBER MECHANICAL FUEL-TO-AIR RATIOS FROM MODEL 250-C20B EMISSION TEST

	Shaft Hp	First Run UP	First Run Down	Second Run Up	Second Run Down
Baseline Liner	5	.0113	.0112	.0113	.0112
Rdgs 232-257	25	.0118	.0118	.0117	.0117
	105	.0145	.0145	.0144	.0145
	168	.0151	.0152	.0151	.0153
	231	.0158	.0158	.0160	.0160
	315	.0180	.0180	.0181	.0179
	420	.0209	-	.0209	-
Prechamber Liner	5	.0110	.0107	.0110	.0109
EX-11987	25	.0116	.0116	.0114	.0118
Rdgs 289-314	105	.0146	.0146	.0146	.0146
	168	.0153	.0152	.0153	.0155
	231	.0160	.0162	.0160	.0162
	315	.0184	.0184	.0185	.0184
	420	.0208	-	.0205	-

A summary of the time at each power level in each of the six profiles is given in Table 93. Gasifier turbine outlet temperature (TOT) versus time curves for each of the six profiles are shown in Figures 169 through 174. Profile I is the most severe profile, having a major portion of the time at high-power levels. In general, each successive profile has less time at high power and more time at the lower-power levels.

The engine with the prechamber combustor system was installed in test cell 140 for the durability testing. DDA's Automatically Controlled Endurance System, Version VI (ACES-VI), was installed in the test cell control room and set up to operate the engine during the durability cycle. The ACES-VI unit was shown in Figure 119.

Photographs of the combustor liner were taken at the conclusion of the durability running. These photographs are presented in Figures 175 and 176. The outer combustion case showed no damage from the 42 hours of cycle running other than the cracking of an inlet air instrumentation boss, which was unreinforced when welded to the thin sheet material.

The combustor liner, No. 17, showed some thermal distortion in the area of the dilution holes where there was little effective cooling. All air-film cooled sections of the liner were in quite good condition. Some small amounts of carbon buildup did occur on the fuel nozzle faces and on the liner swirler vane trailing edges. Additional carbon was found on the inner surface of the prechamber cylinder. There was no noticeable carbon in the reaction, intermediate, or dilution zones. In general, the prechamber combustion system exhibited no significant mechanical deficiencies during the durability testing.

The airblast fuel injector was operated on the secondary (main) airblast fuel system at all times; the pilot line was capped off. Starting was successfully accomplished with the spark igniter mounted through the side of the prechamber cylinder with the plug tip flush with the prechamber tube inside surface.

Multiple Fuels Testing

In addition to the emissions testing of the prechamber combustor on JP-4 reference fuel (MIL-F-5161 Grade 1), it was of interest to evaluate the performance of the combustor and engine when other types of fuels were burned. Therefore, regular grades of JP-4 and JP-5 fuels and a research quantity of oil-shale-derived fuel refined toward a JP-5/Jet-A

TABLE 93. PROFILE SUMMARY FROM DURABILITY TEST

Shaft HP			153	229	270	297	324	346	376	420	
Shaft HP %			36.4	54.5	64.3	70.1	77.1	82.4	89.5	100.0	
TOT	Start GI	FA	1040	1130	1185	1225	1270	1310	1370	1490	Total
Profile No.	min: sec	min: sec	min: sec	min: sec	min: sec	min: sec	min: sec	min: sec	min: sec	min: sec	min: sec
I	1:30	4:00	1:30				3:00		1:30	9:30	21:00
II	1:30	4:00	1:30		1:00		1:30	9:30		2:00	21:00
III	1:30	3:00					2:00	7:00	6:30	1:00	21:00
IV	1:30	3:00					7:00	8:00	1:30		21:00
V	1:30	3:00		1:00	7:00	7:30	1:00				21:00
VI	1:30	1:00	9:00		8:30				1:00		21:00
Total	9:00	18:00	12:00	1:00	16:30	7:30	14:30	24:30	10:30	12:30	126:00
% of Total	7.1	14.3	9.5	.8	13.1	6.0	11.5	19.4	8.3	9.9	100.0
% Above Power Shown	100.0	92.9	78.6	69.0	68.3	55.2	49.2	37.7	18.2	9.9	
20 Periods											
Segment (hr:min)	3:00	6:00	4:00	:20	5:30	2:30	4:50	8:10	3:30	4:10	42:00
Above Power (hr:min)	42:00	39:00	33:00	29:00	28:40	23:10	20:40	15:50	7:40	4:10	

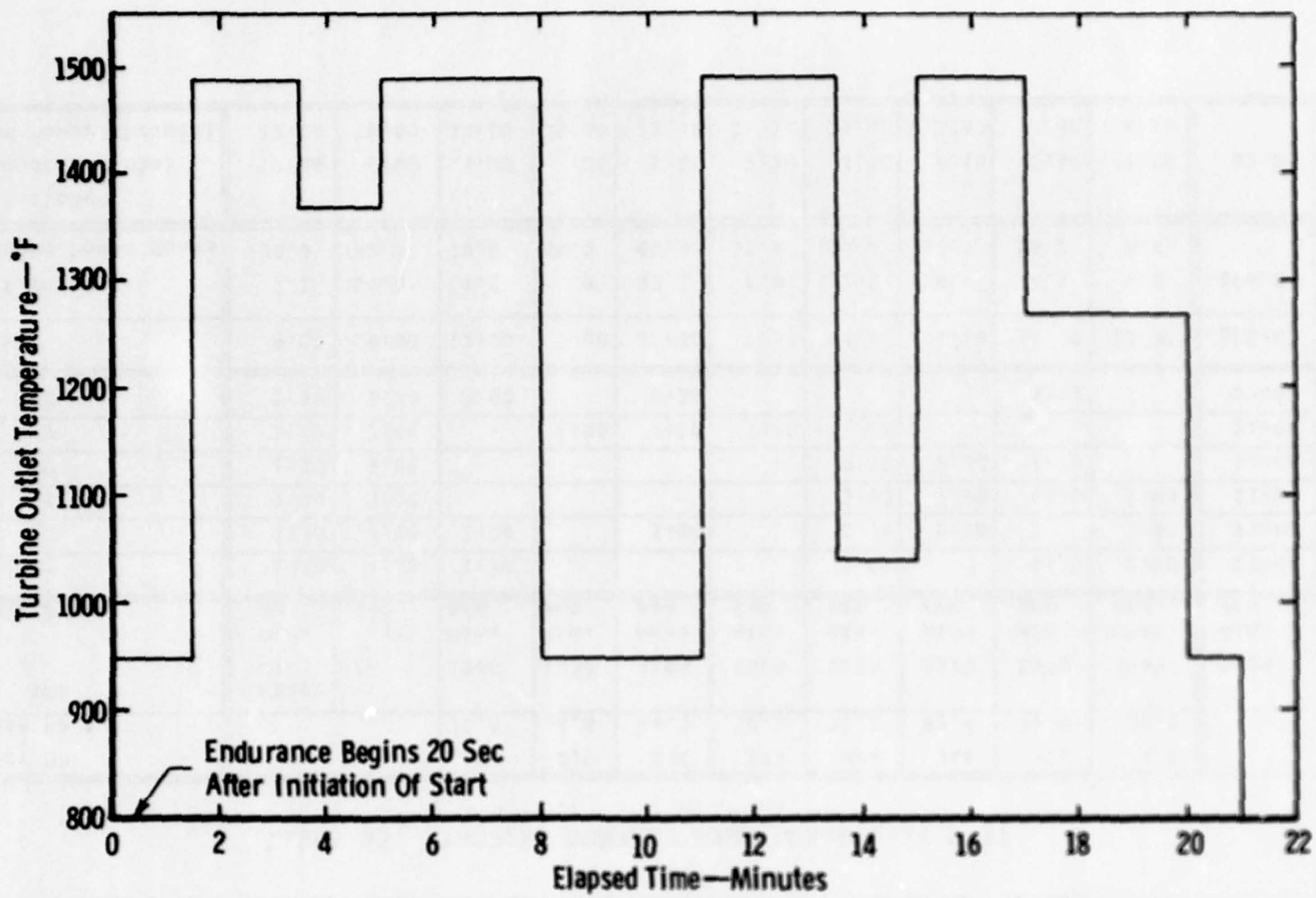


Figure 169. Prechamber Liner Engine Durability Test—Profile I.

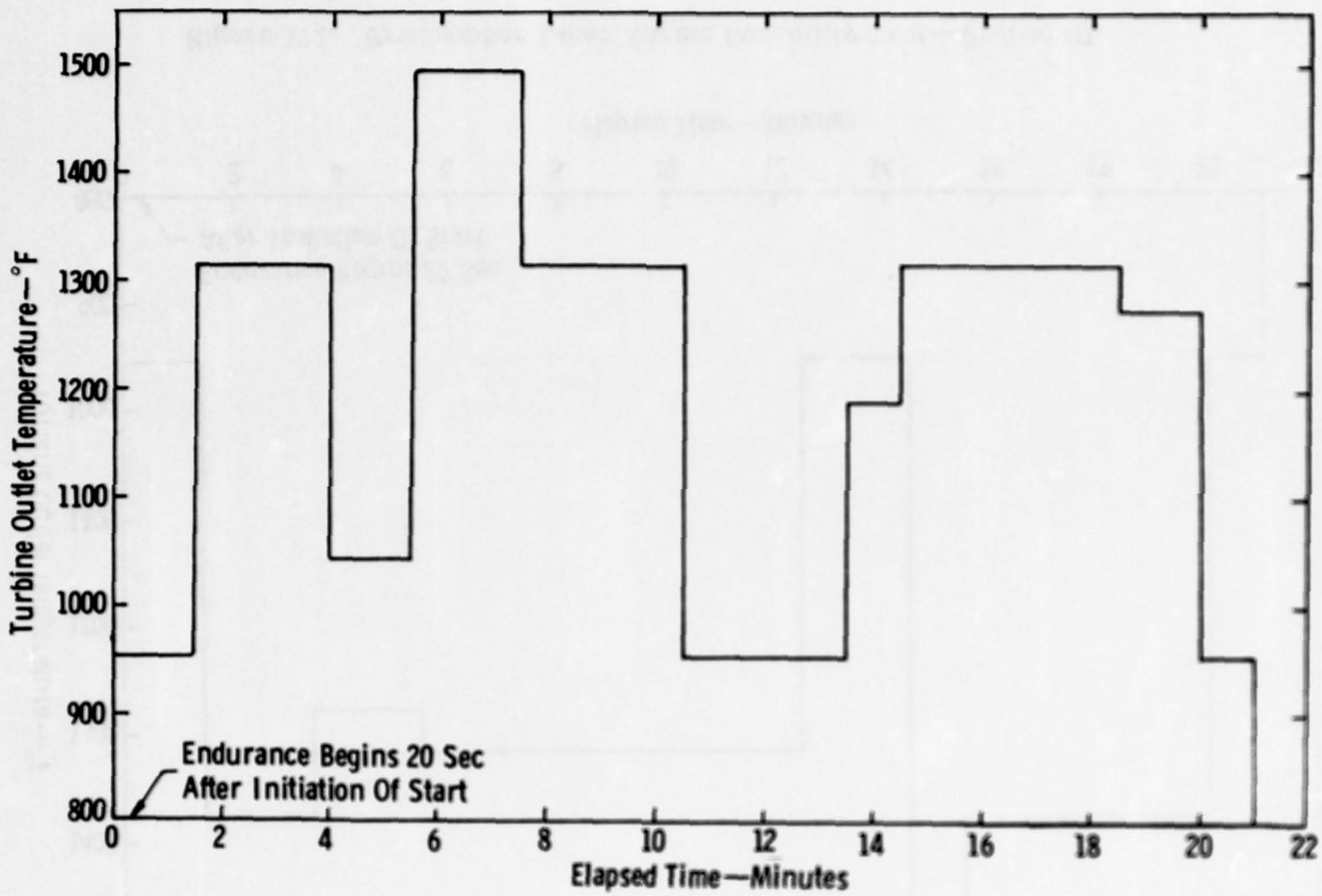


Figure 170. Prechamber Liner Engine Durability Test—Profile II.

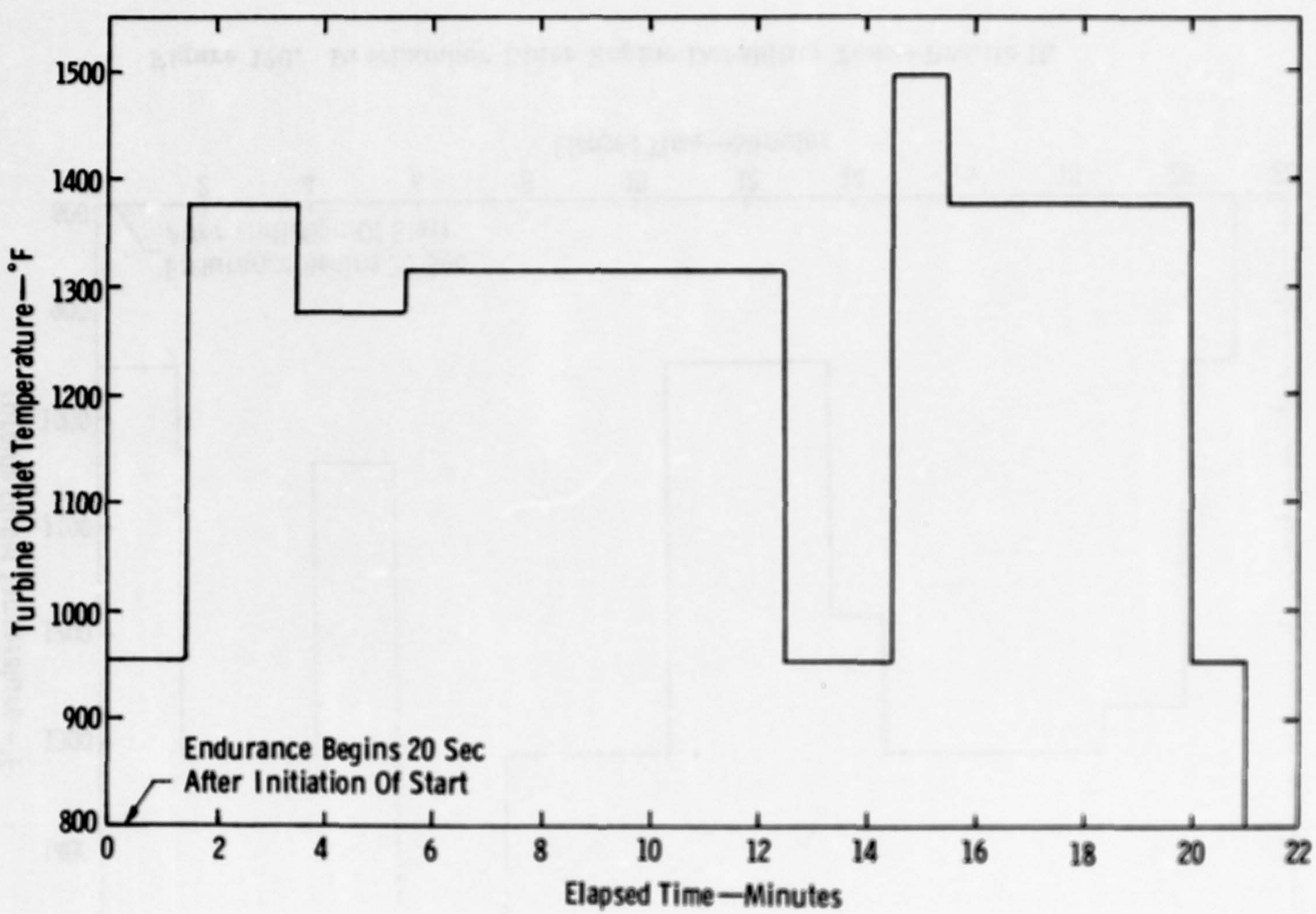


Figure 171. Prechamber Liner Engine Durability Test—Profile III.

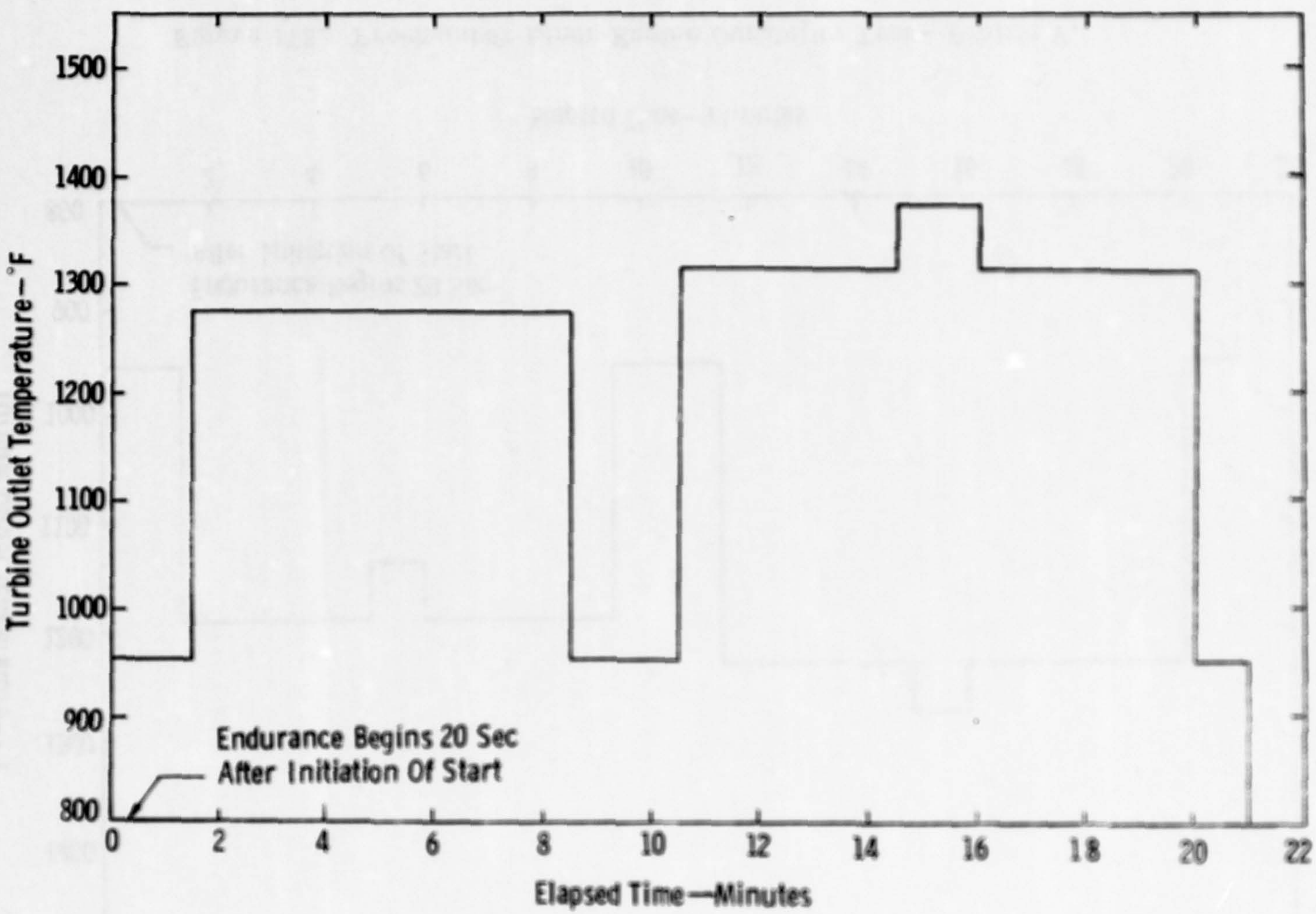


Figure 172. Prechamber Liner Engine Durability Test—Profile IV.

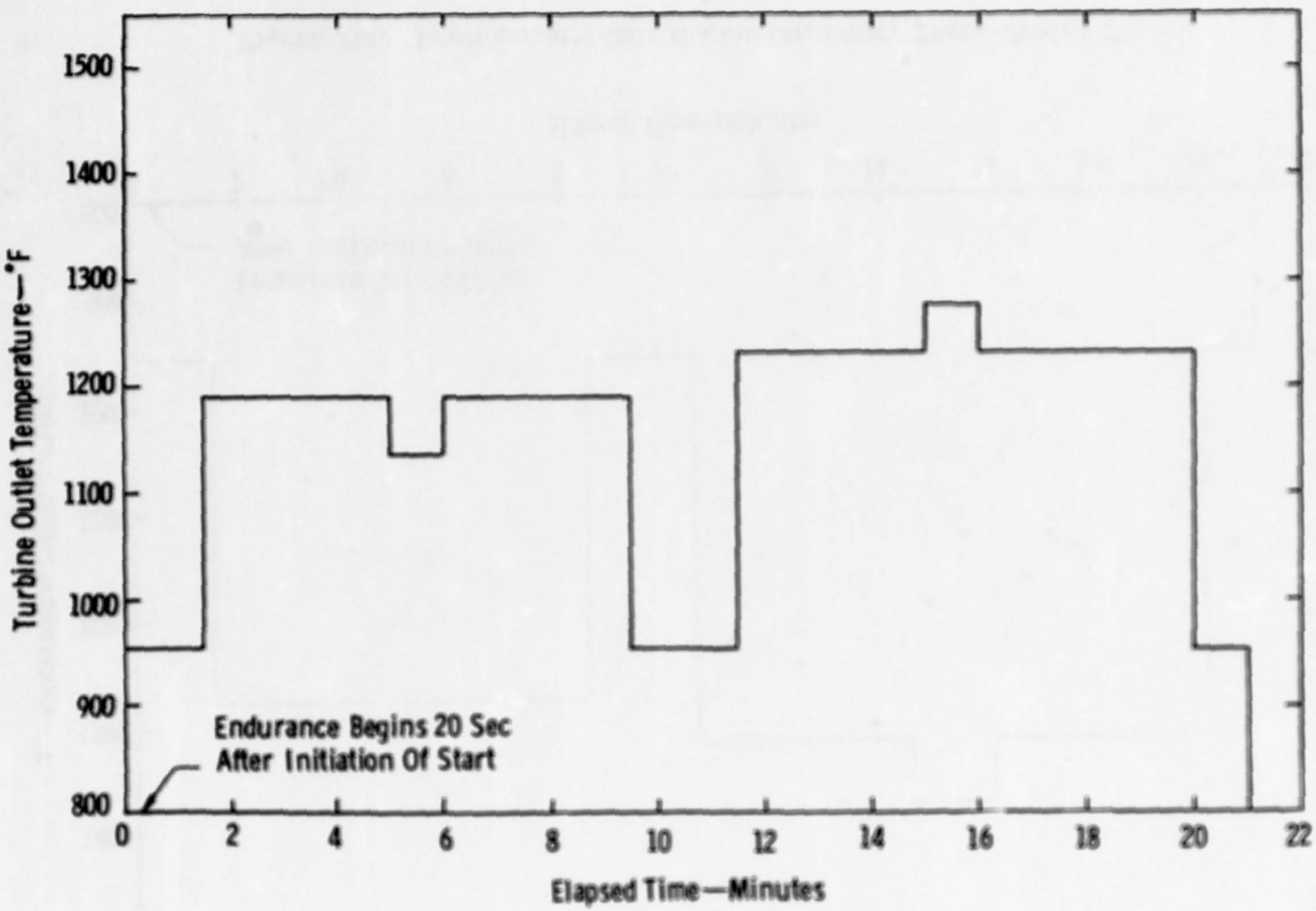


Figure 173. Prechamber Liner Engine Durability Test—Profile V.

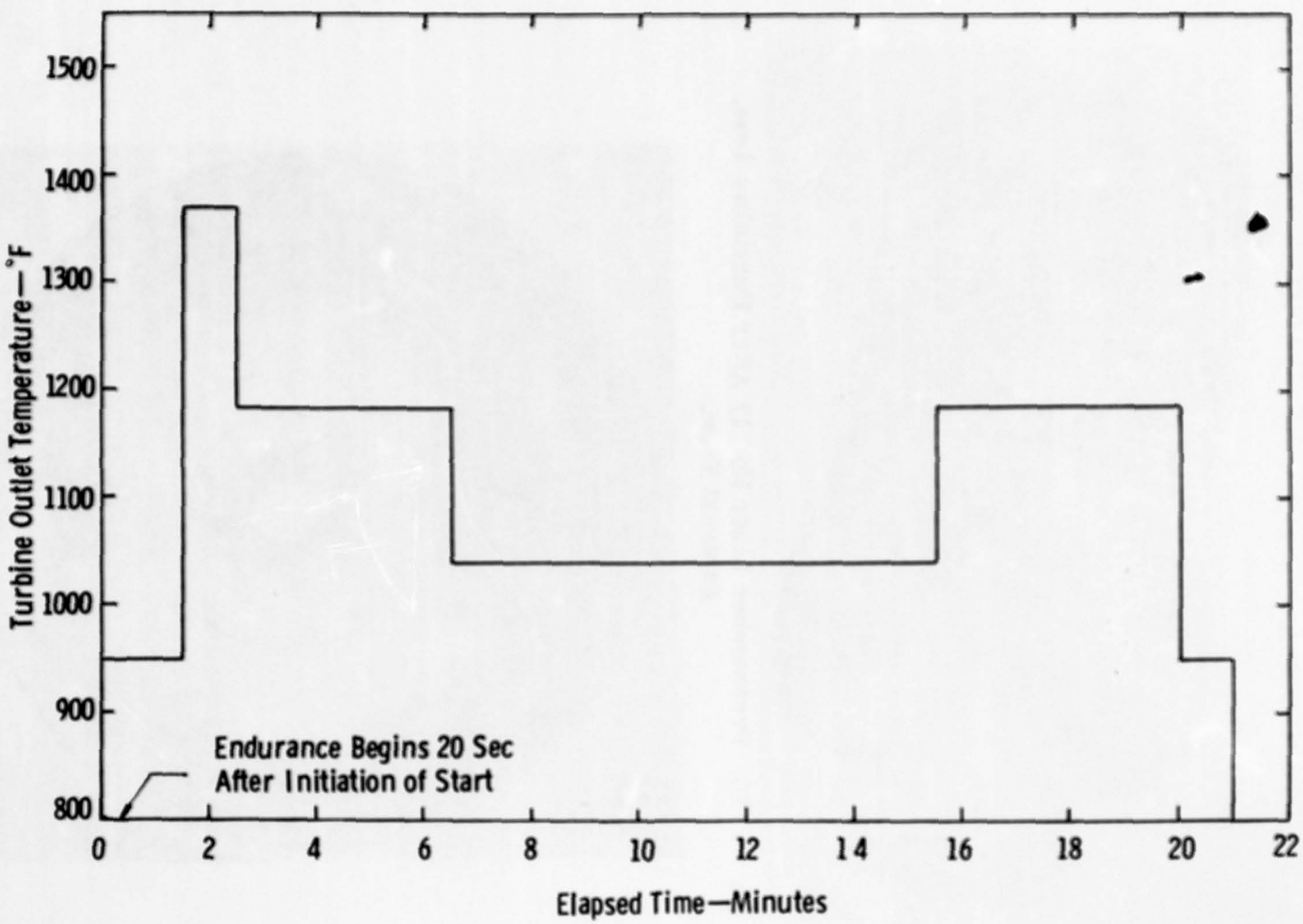


Figure 174. Prechamber Liner Engine Durability Test—Profile VI.

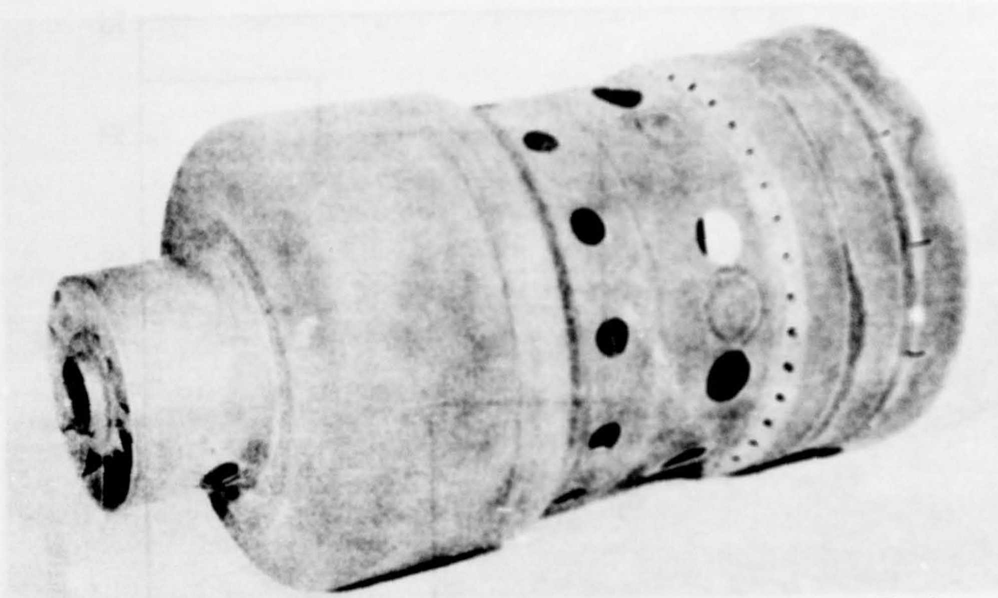


Figure 175. Prechamber Liner No. 17 After Durability Test, External View.

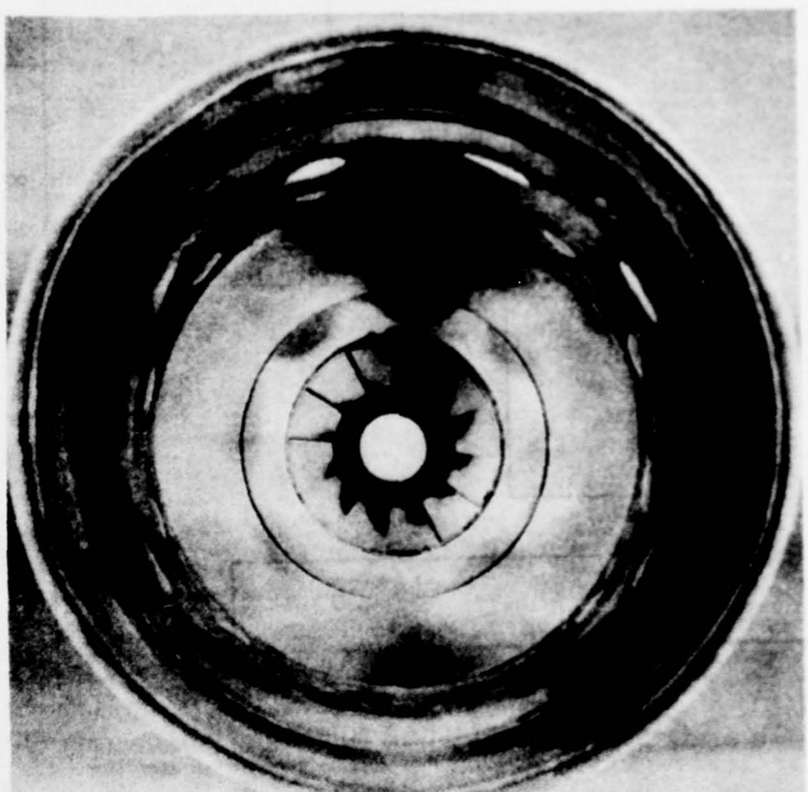


Figure 176. Prechamber Liner No. 17 After Durability Test, Internal View.

specification were tested in the prechamber combustor. The shale fuel was supplied by the Navy to DDA through the U.S. Army. The fuel was refined from crude shale oil produced by the Paraho process and mined from the Naval oil shale reserve at Anvil Points, Colorado.[5]

Analyses of fuel samples taken from these tests are presented in Tables 94 through 96 for JP-4, JP-5, and JP-5/Jet-A Shale. Table 96 gives two analyses of the oil shale fuel. One analysis was performed at DDA while the other was performed at the U.S. Army Fuels and Lubricants Research Laboratory (USAFLRL), San Antonio, Texas.[6]

Engine performance and exhaust emissions using each fuel were recorded at approximately 1, 6, 25, 40, 55, 75, and 100% power in both ascending and descending power sequences. A summary of these data is shown in Tables 97 through 99. In each of these tabulations, both chemical and mechanical fuel-air ratios are provided, as well as the ratio of the chemically derived value to the mechanical. These results, summarized in Table 100, show that, on the average, chemical fuel-air ratios were 5% higher than the mechanically derived values.

When comparing the prechamber combustor system exhaust emissions from the various fuel runs, one additional set of data is included in the plots, the emissions reported previously using JP-4 reference fuel. Fuel analysis results from this testing, using JP-4 reference fuel, are summarized in Table 88. Prechamber engine performance and exhaust emissions from the engine testing of the multiple fuels are presented in Figures 177 through 190 for JP-4 reference, JP-4 regular, JP-5 regular, and JP-5/Jet-A oil-shale-derived fuels.

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[5] The Production and Refining of 10,000 Barrels of Crude Shale Oil into Military Fuels. Applied Systems Corporation, Contract N00014-75-C-0055. Navy Energy and Natural Resources, R&D Office with the Office of Naval Research, 1975.

[6] Moses, C. A. Analysis of Shale Oil Derived Fuel. U.S. Army Fuels and Lubricants Research Laboratory, 8500 Culebra Road, P.O. Drawer 28510, San Antonio, Texas, 78284. Personal Correspondence to K. F. Smith, U.S. Army AMRDL, Ft. Eustis, Virginia 23604, September 1975.

TABLE 94. FUEL SAMPLE PROPERTIES FOR JP-4 REGULAR FUEL, MIL-T-5624J.

Parameter	Sample Results	Specification
Distillation		
I.B.P., °F	158	
5% recovered, °F	210	
10%	228	
20%	250	290 max
30%	272	
40%	295	
50%	321	370 max
60%	346	
70%	374	
80%	409	
90%	443	470 max
95%	465	
End Point, °F	483	
Recovered, %	98.3	
Residue, %	1.1	1.5 max
Loss, %	0.6	1.5 max
10% evap., °F		
20%		
50%		
90%		
Gravity, °API	54.0	45.0-57.0
Aniline Point, °F	140.0	
Aniline-Gravity Product	7560	5250 min
Net Heat of Combustion BTU/lb (Calculated)	18,770	18,400 min
Reid Vapor Pressure, psi	1.8	2.0-3.0
Smoke Point, mm	29.5	
Flash Point, °F		
Corrosion, Copper Strip	1b	1b max
Sulfur, % by wt.	0.04	0.40 max
Hydrogen, % by wt.	14.685	
H/C Atom Ratio	2.051	
Aromatics, % by vol.	12.1	25.0 max
Olefins, % by vol.	1.8	5.0 max

TABLE 95. FUEL SAMPLE PROPERTIES FOR JP-5 REGULAR FUEL, MIL-T-5624J.

Parameter	Sample Results	Specification
Distillation		
I.B.P., °F	358	
5% recovered, °F	384	
10%	389	400 max
20%	402	
30%	410	
40%	418	
50%	426	
60%	434	
70%	444	
80%	456	
90%	473	
95%	488	
End Point, °F	505	550 max
Recovered, %	98.2	
Residue, %	1.3	1.5 max
Loss, %	0.5	1.5 max
10% evap., °F		
20%		
50%		
90%		
Gravity, °API	43.4	36.0-48.0
Aniline Point, °F	148.6	
Aniline-Gravity Product	6449	4500 min
Net Heat of Combustion BTU/lb (Calculated)	18,588	18,300 min
Reid Vapor Pressure, psi		
Smoke Point, mm	21.7	19.0 min
Flash Point, °F	140	140 min
Corrosion, Copper Strip	2b	1b max
Sulfur, % by wt.	0.05	0.40
Hydrogen, % by wt.	14.097	
H/C Atom Ratio	1.955	
Aromatics, % by vol.	15.8	25.0 max
Olefins, % by vol.	2.9	5.0 max

TABLE 96. FUEL SAMPLE PROPERTIES FOR SHALE OIL DERIVED JP-5/JET-A FUEL

Parameter	Sample Results DDA	USAFLRL	Specification JP-5 MIL-T-5424J	Jet A ASTM D1655
Distillation				
I.B.P., °F	327	326		
5% recovered, °F	370	366		
10%	375	378	400 max	440 max
20%	395	392		
30%	408	403		
40%	419	412		
50%	433	426		450 max
60%	446	439		
70%	460	452		
80%	476	468		
90%	498	491		
95%	523	512		
End Point, °F	555	542	550 max	550 max
Recovered, %	98.3	98.7		
Residue, %	1.1	1.2	1.5 max	1.5 max
Loss, %	0.6	0.1	1.5 max	1.5 max
10% evap., °F		378		
20%		392		
50%		426		
90%		491		
Gravity, °API	44.1	44.2	36.0-48.0	37.0-51.0
Aniline Point, °F	142.5	143.6		
Aniline-Gravity Product	6284	6347	4500 min	
Net Heat of Combustion BTU/lb (Calculated)	18,574	19,451	18,300min	18,400min
Reid Vapor Pressure, psi				
Smoke Point, mm	18.7		19.0 min	25.0 min
Flash Point, °F	122	126	140 min	105-150
Corrosion, Copper Strip	1a	1a	1b max	1b max
Sulfur, % by wt.	0.03	.00	0.40 max	0.30 max
Hydrogen, % by wt.	14.073	14.095		
H/C Atom Ratio	1.952	1.955		
Aromatics, % by vol.	27.2	21.1	25.0 max	20.0 max
Olefins, % by vol.	3.8	3-5	5.0 max	
Nitrogen, % by wt.	0.10	0.09		

TABLE 97. EXHAUST EMISSIONS FROM ENGINE TESTING OF PRECHAMBER LINER OPERATING ON JP-4 REGULAR FUEL FINAL TEST.

ROG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
328.	29.0	163.0	55.0	2.42	64.3	1.0	0.01201	0.01089	1.103	99.449	13.282	2.566	3.881	5.1	1.2
329.	31.0	186.0	50.0	2.55	67.9	1.0	0.01267	0.01131	1.120	99.454	14.380	2.213	3.936	27.0	6.4
330.	44.0	122.0	48.0	3.01	116.9	1.0	0.01493	0.01456	1.025	99.634	8.019	1.807	4.750	107.2	25.5
331.	50.0	92.0	45.5	3.08	142.7	1.0	0.01526	0.01532	0.996	99.692	5.917	1.676	5.282	172.4	41.0
332.	62.0	82.0	35.5	3.52	169.7	1.0	0.01746	0.01598	1.093	99.766	4.620	1.145	5.737	237.9	56.6
333.	74.5	75.0	35.5	3.83	208.9	3.0	0.01902	0.01814	1.049	99.789	3.885	1.053	6.338	316.4	75.3
334.	78.0	68.0	37.3	3.89	237.8	4.0	0.01932	0.01969	0.981	99.794	3.469	1.090	6.535	375.1	89.3
335.	73.8	71.0	30.5	3.77	209.1	3.0	0.01871	0.01826	1.025	99.804	3.737	0.919	6.380	317.1	75.5
336.	62.5	78.5	28.0	3.50	169.0	1.0	0.01736	0.01600	1.085	99.791	4.449	0.909	5.818	234.3	55.8
337.	54.0	93.0	22.0	3.18	140.2	1.0	0.01575	0.01523	1.034	99.772	5.798	0.785	5.529	168.4	40.1
338.	45.0	118.0	20.5	2.85	113.2	1.0	0.01411	0.01428	0.988	99.715	8.198	0.816	5.135	104.2	24.8
339.	32.0	163.0	21.5	2.51	73.4	1.0	0.01244	0.01149	1.083	99.599	12.826	0.969	4.136	34.1	8.1
340.	30.0	147.0	19.0	2.48	69.1	1.0	0.01228	0.01126	1.091	99.634	11.715	0.867	3.927	7.6	1.8

TABLE 98. EXHAUST EMISSIONS FROM ENGINE TESTING OF PRECHAMBER LINER OPERATING ON JP-5 REGULAR FUEL, FINAL TEST.

RDG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
315.	30.0	195.0	37.0	2.54	64.4	7.0	0.01253	0.01147	1.092	99.482	15.241	1.656	3.851	0.7	0.2
316.	32.0	205.0	28.5	2.65	66.8	10.0	0.01307	0.01156	1.131	99.516	15.362	1.223	3.939	23.6	5.6
317.	37.0	163.0	30.2	2.98	117.5	48.0	0.01469	0.01457	1.008	99.626	10.887	1.155	4.059	102.5	24.4
318.	62.0	110.0	27.7	3.22	147.7	1.0	0.01585	0.01570	1.010	99.726	6.815	0.983	6.309	177.6	42.3
319.	68.0	91.0	36.0	3.51	173.9	1.0	0.01730	0.01623	1.066	99.748	5.175	1.172	6.352	233.0	55.5
320.	78.0	80.0	36.7	3.78	214.1	4.0	0.01864	0.01846	1.010	99.774	4.227	1.110	6.769	317.0	75.5
321.	84.0	78.0	40.5	4.10	239.7	11.0	0.02025	0.01975	1.025	99.782	3.800	1.130	6.722	374.2	89.1
322.	74.0	78.0	30.7	3.79	212.2	5.0	0.01869	0.01832	1.020	99.794	4.111	0.927	6.406	314.6	74.9
323.	65.0	88.0	36.5	3.49	171.6	1.0	0.01719	0.01607	1.070	99.750	5.033	1.196	6.107	233.4	55.6
324.	58.0	108.0	59.0	3.18	144.8	1.0	0.01567	0.01556	1.007	99.630	6.768	2.117	5.970	167.0	39.8
325.	41.0	165.0	21.0	2.99	117.7	1.0	0.01473	0.01467	1.004	99.653	10.987	0.801	4.484	102.5	24.4
326.	32.0	192.0	17.5	2.60	70.4	12.0	0.01281	0.01165	1.100	99.572	14.676	0.766	4.017	31.6	7.5
327.	30.0	155.0	20.5	2.52	66.3	7.0	0.01240	0.01116	1.111	99.615	12.237	0.927	3.890	0.7	0.2

TABLE 99. EXHAUST EMISSIONS FROM ENGINE TESTING OF PRECHAMBER LINER OPERATING ON SHALE DERIVED JP-5/JET-A FUEL, FINAL TEST.

RDG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
367.	42.0	187.0	19.2	2.40	62.2	14.0	0.01182	0.01117	1.058	99.533	15.481	0.913	5.711	8.9	2.1
368.	47.5	201.0	22.7	2.62	65.9	17.0	0.01291	0.01161	1.112	99.531	15.243	0.986	5.917	29.0	6.9
369.	67.0	108.0	21.7	2.98	118.1	1.0	0.01465	0.01476	0.993	99.725	7.231	0.832	7.368	111.7	26.6
370.	76.0	91.0	20.5	3.32	146.8	1.0	0.01634	0.01581	1.033	99.776	5.474	0.706	7.509	172.4	41.0
371.	85.0	79.0	21.0	3.57	173.4	1.0	0.01758	0.01621	1.084	99.802	4.422	0.673	7.815	235.7	56.1
372.	96.0	71.8	21.0	3.98	217.2	1.0	0.01963	0.01885	1.041	99.827	3.607	0.604	7.921	318.6	75.9
373.	99.9	70.5	19.5	4.15	238.5	1.0	0.02048	0.01980	1.034	99.838	3.397	0.538	7.906	363.6	86.6
374.	92.5	71.5	18.4	3.95	215.9	1.0	0.01947	0.01875	1.039	99.834	3.619	0.533	7.690	318.9	75.9
375.	85.5	79.0	15.0	3.61	178.1	8.0	0.01777	0.01676	1.061	99.821	4.374	0.476	7.775	236.2	56.2
376.	77.5	90.0	15.3	3.30	143.2	3.0	0.01623	0.01540	1.054	99.791	5.448	0.530	7.705	171.1	40.7
377.	68.0	110.0	14.0	3.00	121.7	3.0	0.01475	0.01524	0.968	99.749	7.317	0.533	7.430	112.3	26.7
378.	49.0	198.0	13.3	2.63	62.0	24.0	0.01296	0.01076	1.204	99.572	14.966	0.576	6.083	30.4	7.2
379.	45.5	193.0	14.5	2.48	62.8	16.0	0.01221	0.01112	1.098	99.553	15.466	0.665	5.989	10.9	2.6

TABLE 100. COMPARISON OF CHEMICAL AND MECHANICAL FUEL-TO-AIR RATIOS FOR PRECHAMBER LINER OPERATING ON DIFFERENT FUELS.

JP-5 REGULAR

RATIO OF F/A C/M AVG = 1.050
SIGMA = 0.046
1 SIGMA RANGE = 1.004 1.096
2 SIGMA RANGE = 0.958 1.143
3 SIGMA RANGE = 0.912 1.189

RDG NO	FAC/FAM
325	1.0044
324	1.0071
317	1.0081
320	1.0098
318	1.0099
322	1.0200
321	1.0252
319	1.0657
323	1.0700
315	1.0921
326	1.0997
327	1.1110
316	1.1307

CHEMICAL PROPERTIES OF THE FUEL USED

C1 MOL WT	H/C	HC
13.982006	1.955364	18588.

JP-4 REGULAR

RATIO OF F/A C/M AVG = 1.052
SIGMA = 0.047
1 SIGMA RANGE = 1.005 1.099
2 SIGMA RANGE = 0.958 1.145
3 SIGMA RANGE = 0.911 1.192

RDG NO	FAC/FAM
334	0.9813
338	0.9884
331	0.9963
335	1.0249
330	1.0254
337	1.0344
333	1.0486
339	1.0827
336	1.0848
340	1.0907
332	1.0928
328	1.1027
329	1.1198

CHEMICAL PROPERTIES OF THE FUEL USED

C1 MOL WT	H/C	HC
14.078487	2.051080	18733.

JP-5/JET-A SHALE

RATIO OF F/A C/M AVG = 1.060
SIGMA = 0.058
1 SIGMA RANGE = 1.002 1.118
2 SIGMA RANGE = 0.943 1.177
3 SIGMA RANGE = 0.885 1.235

RDG NO	FAC/FAM
377	0.9678
369	0.9927
370	1.0332
373	1.0343
374	1.0386
372	1.0412
376	1.0541
367	1.0580
375	1.0605
371	1.0843
379	1.0983
368	1.1123
378	1.2042

CHEMICAL PROPERTIES OF THE FUEL USED

C1 MOL WT	H/C	HC
13.978184	1.951572	18601.

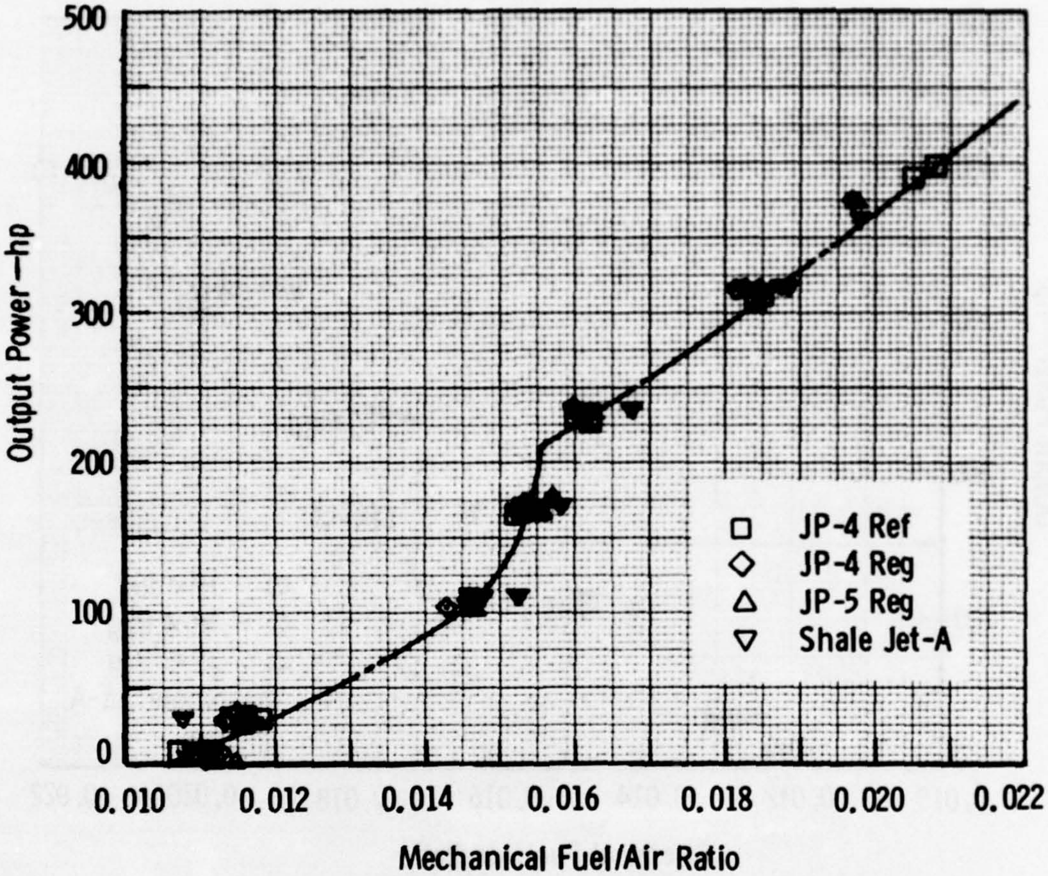

Figure 177. Prechamber Liner Multiple Fuels Engine Test, Output Power at Mechanical Fuel-to-Air Ratios.

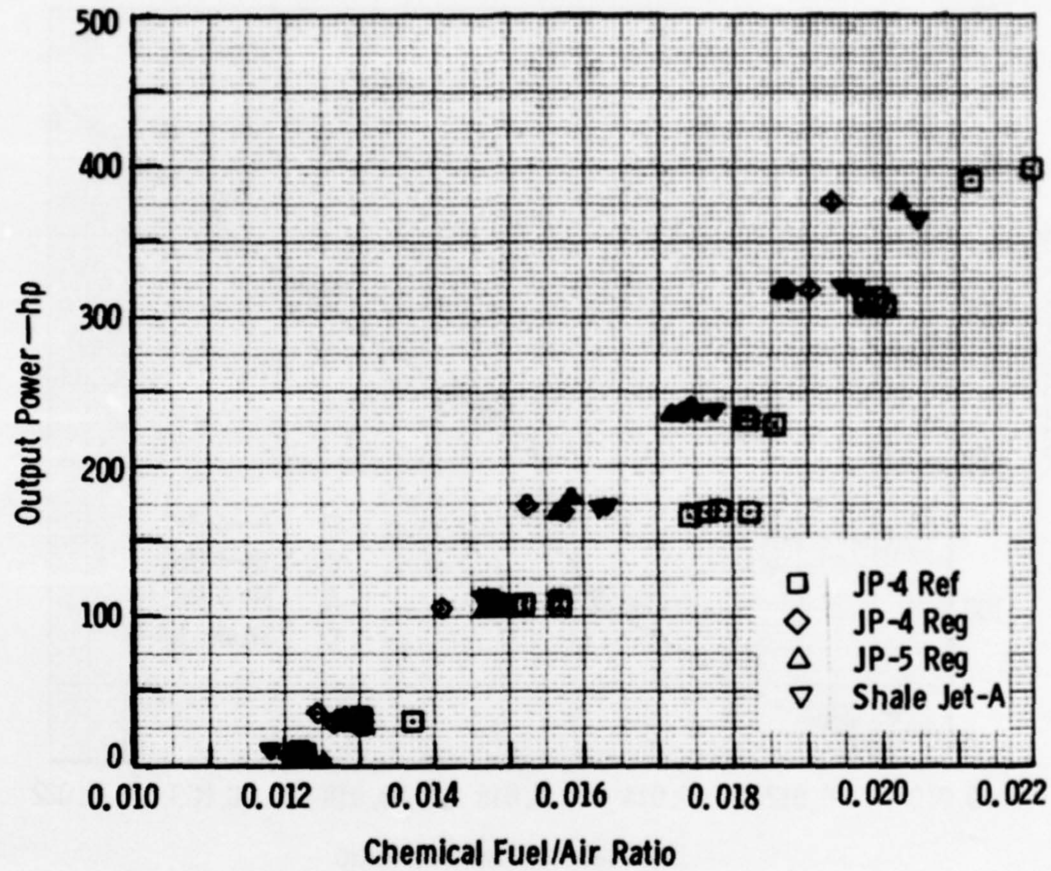

Figure 178. Prechamber Liner Multiple Fuels Engine Test, Output Power at Chemical Fuel-to-Air Ratios.

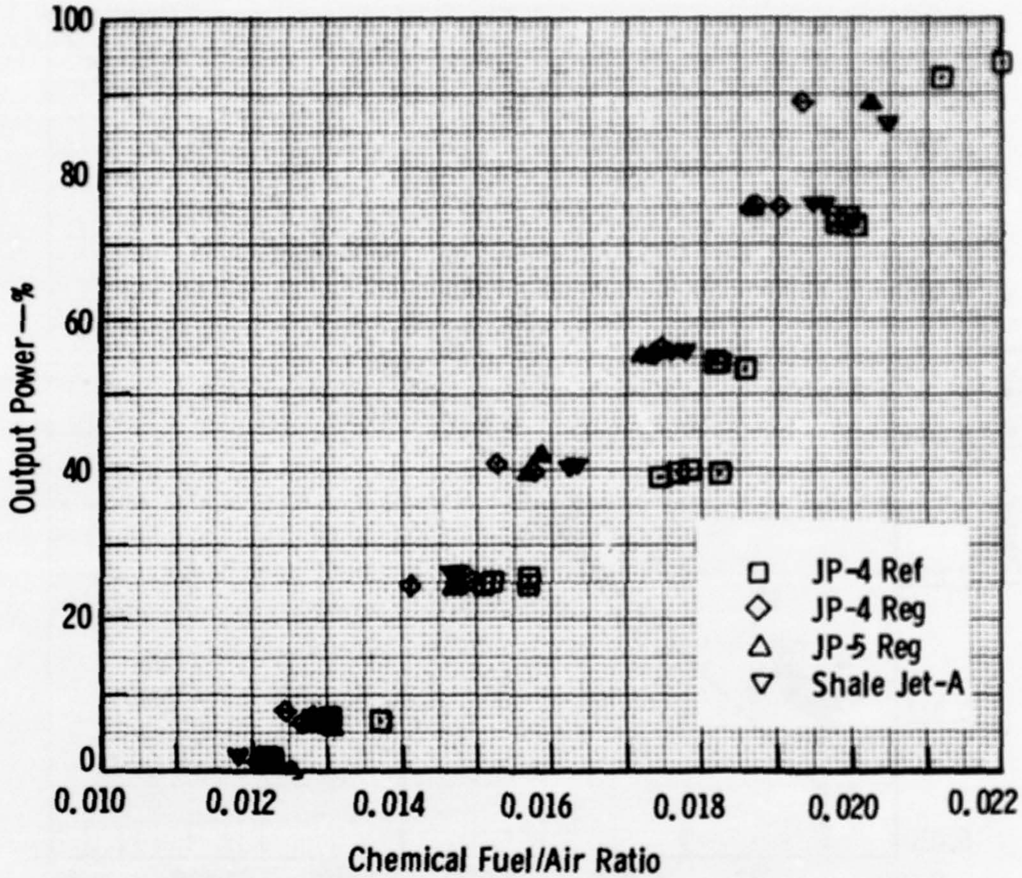

Figure 179. Prechamber Liner Multiple Fuels Engine Test, Percent Output Power at Chemical Fuel-to-Air Ratios.

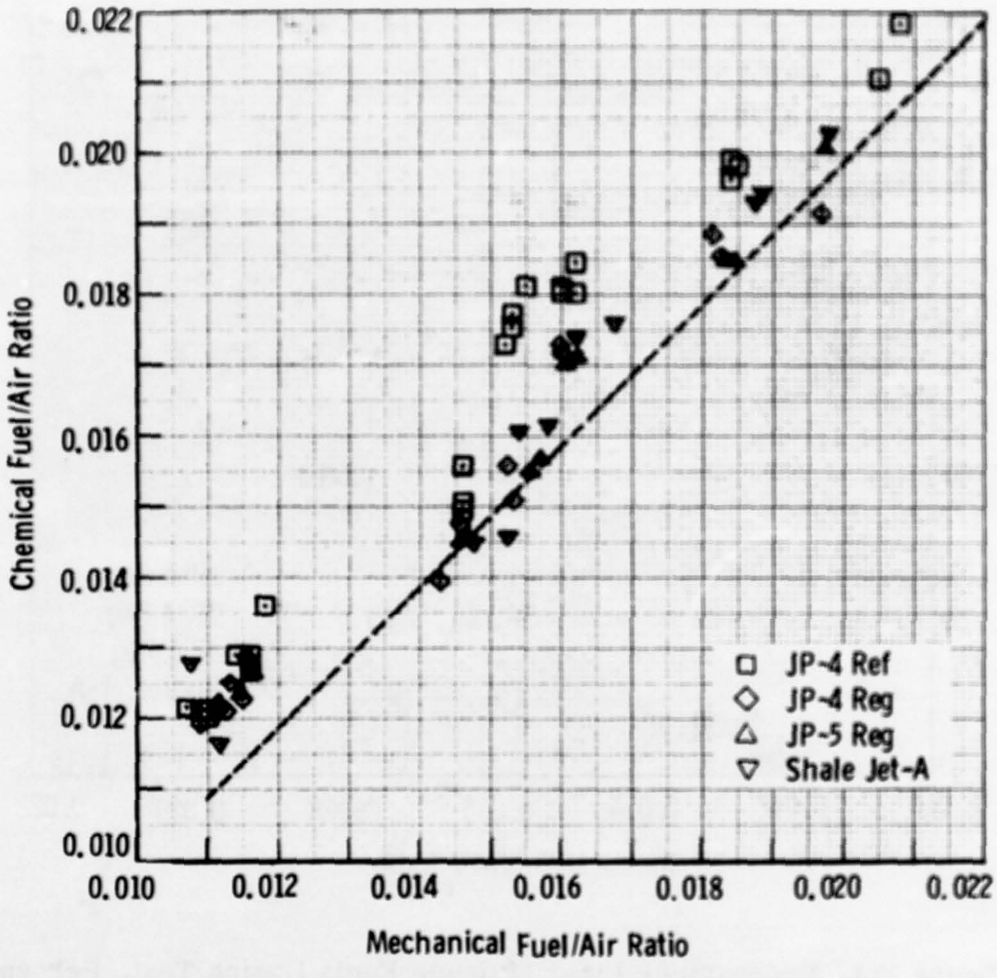

Figure 180. Prechamber Liner Multiple Fuels Engine Test, Mechanical and Chemical Fuel-to-Air Ratios.

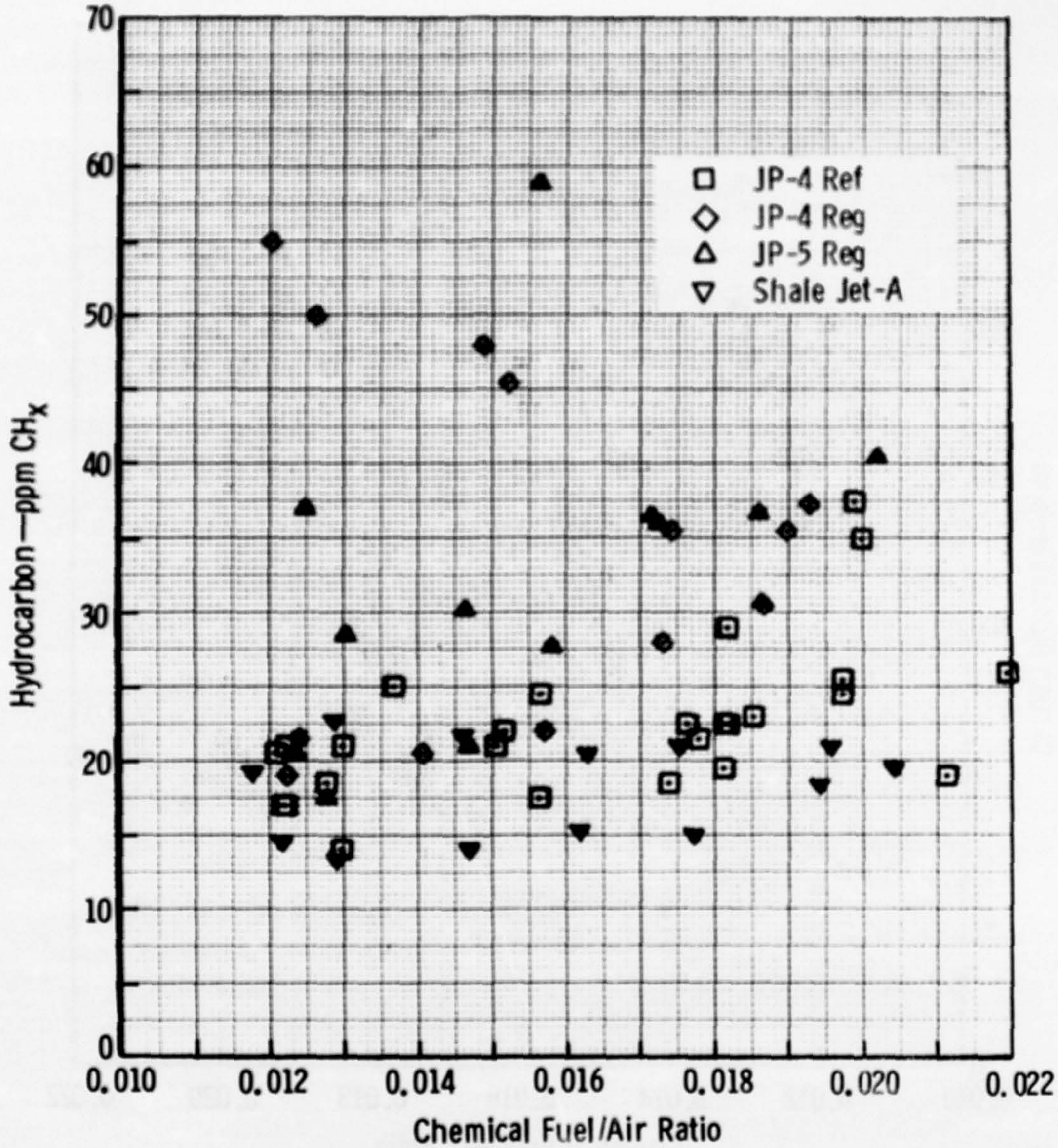

Figure 181. Prechamber Liner Multiple Fuels Engine Test, Unburned Hydrocarbons at Chemical Fuel-to-Air Ratios.

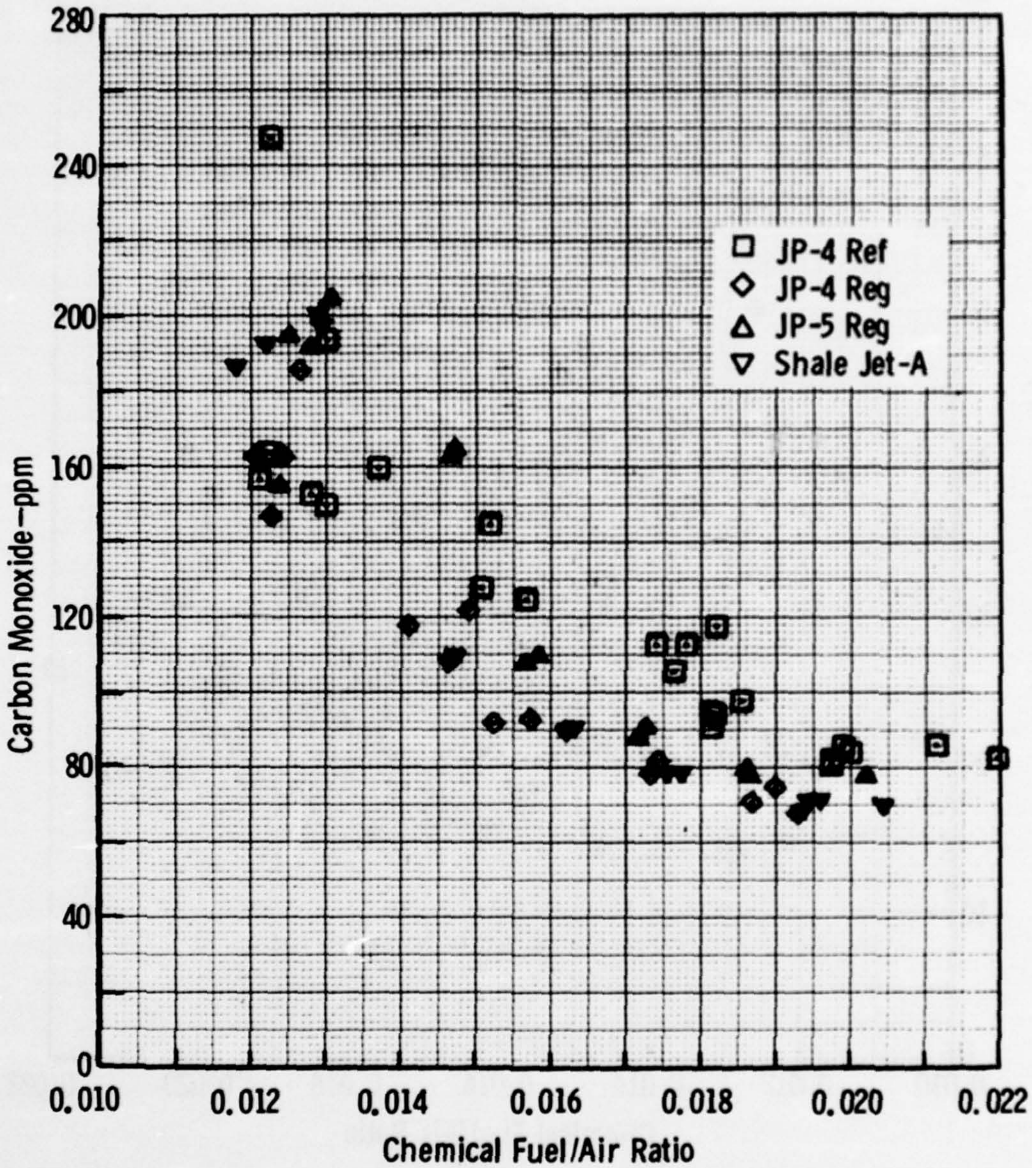

Figure 182. Prechamber Liner Multiple Fuels Engine Test, Carbon Monoxide at Chemical Fuel-to-Air Ratios.

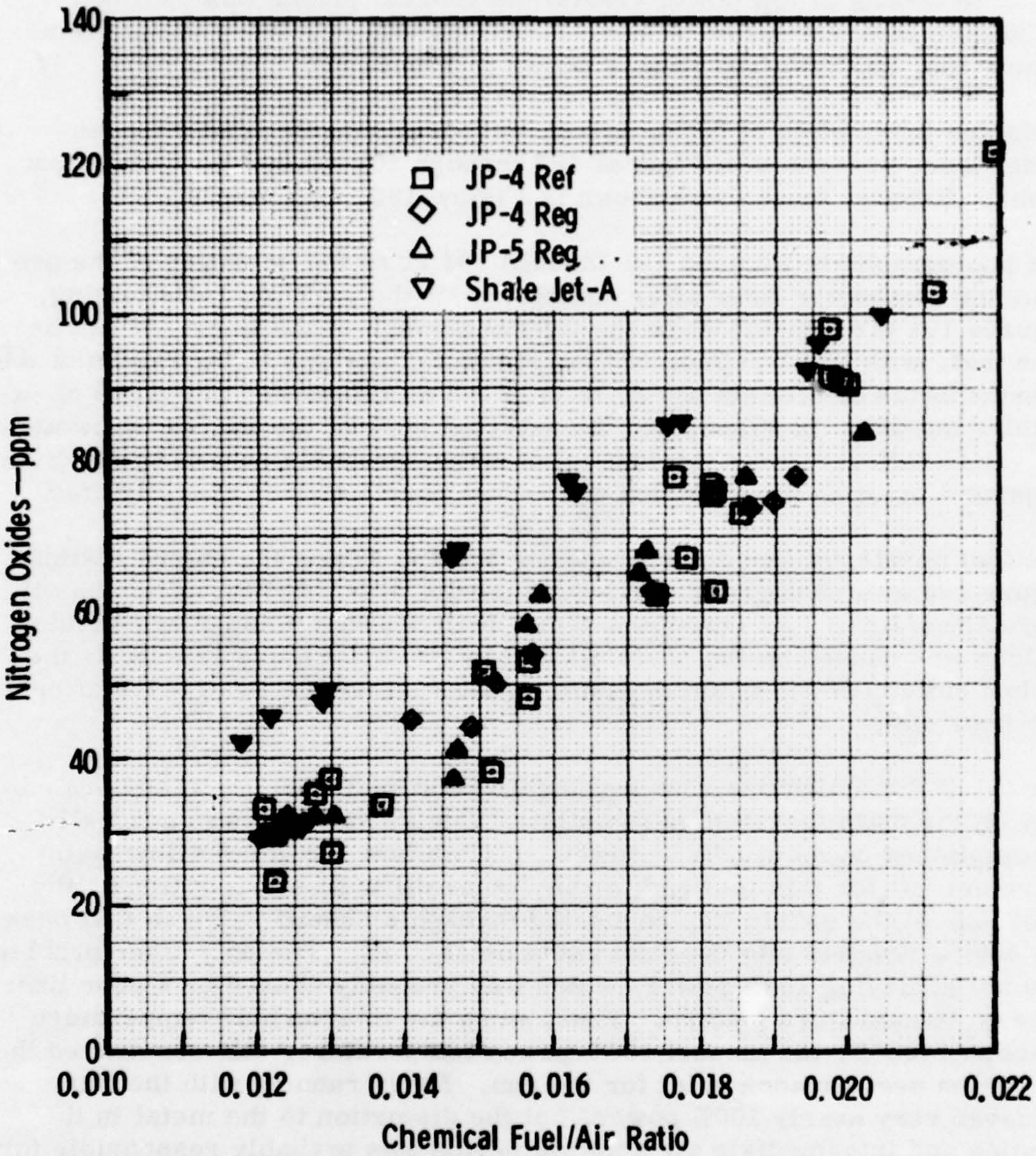

Figure 183. Prechamber Liner Multiple Fuels Engine Test, Total Nitrogen Oxides at Fuel-to-Air Ratios.

A plot of smoke number as a function of chemical fuel-air ratio is given in Figure 184. If the four smoke numbers above 25 are ignored (because of the improper seating of the flame during the JP-4 reference testing and the JP-5 testing at low power levels) the exhaust smoke was well below the visible limit for all of the fuels. Combustion efficiency is shown in Figure 185, and fuel flow rate is shown in Figure 186.

Emission index plots of hydrocarbon, carbon monoxide, and nitrogen oxides were presented in Figures 187 through 189 against percent output power. Exhaust smoke was shown in Figure 190.

The photographs in Figures 191 through 194 show the condition of the prechamber combustor liner after completion of the multiple fuels testing. Figures 191 through 193 show the lateral surface of the liner. It can be seen that, with the exception of the cylindrical surface in the region of the intermediate and dilution holes, none of the metal showed any signs of excessive heating. In Figure 194 the external view of the swirler shows that the vanes suffered some mechanical damage, probably caused by liner alignment prior to the insertion of the fuel nozzle and/or spark igniter.

The fuel nozzle showed signs of carbon buildup during the engine testing. Figure 195 is a photograph of the fuel nozzle, EX-115870C, after the oil shale JP-5/Jet-A fuel emissions test. It is not known how much of this buildup was caused by the shale oil fuel by itself. Figure 196 shows the carbon buildup of JP-4 fuel deposits on airblast nozzle EX-114779 after a two-hour test.

For all of the emissions running, the airblast fuel injector was operated only on the main fuel system (no pilot). Engine start-up was generally accomplished on main only. However, JP-5 fuel would not allow main start-up; so, for this fuel and for any other difficult starting times, the pilot side of the nozzle was connected through a shutoff valve so that once the engine reached idle the pilot could be shut off. The only other problem was not achieving 100% power, which was probably caused by a poor liner exhaust temperature pattern. Thus, when the interturbine temperature reached 1490°F, the normal 100% power temperature, this constituted the maximum performance point for the run. Early running with the liner achieved very nearly 100% power, but the distortion to the metal in the dilution and intermediate air addition region was probably responsible for the deterioration of the liner exhaust temperature pattern and thus the higher than normal interturbine temperature.

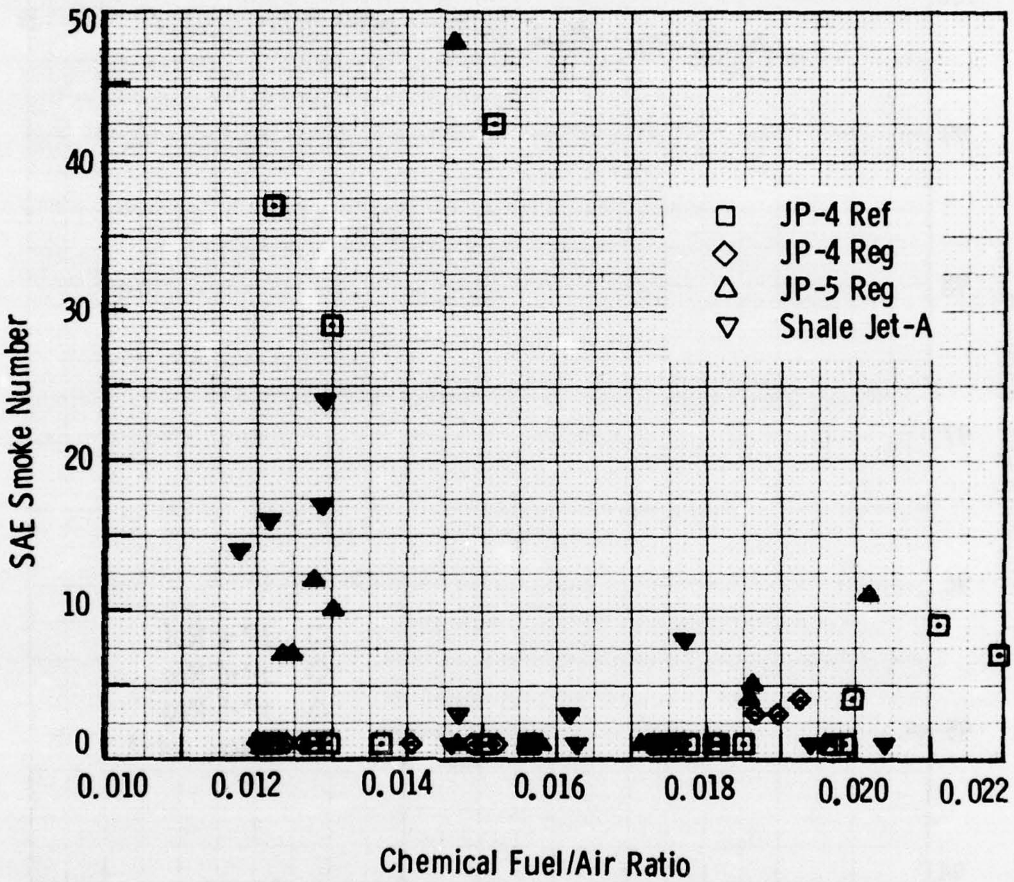

Figure 184. Prechamber Liner Multiple Fuels Engine Test, Exhaust Smoke at Fuel-to-Air Ratios.

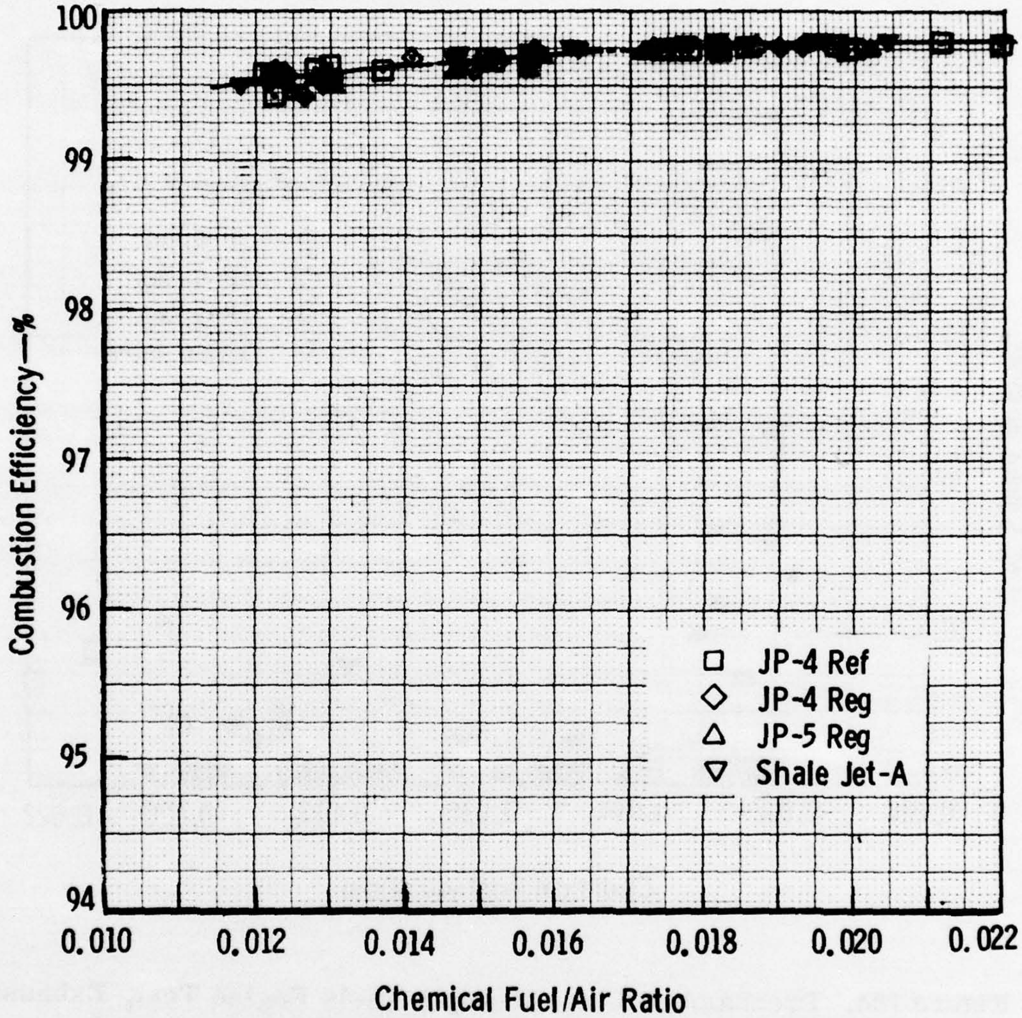

Figure 185. Prechamber Liner Multiple Fuels Engine Test, Combustion Efficiency at Fuel-to-Air Ratios.

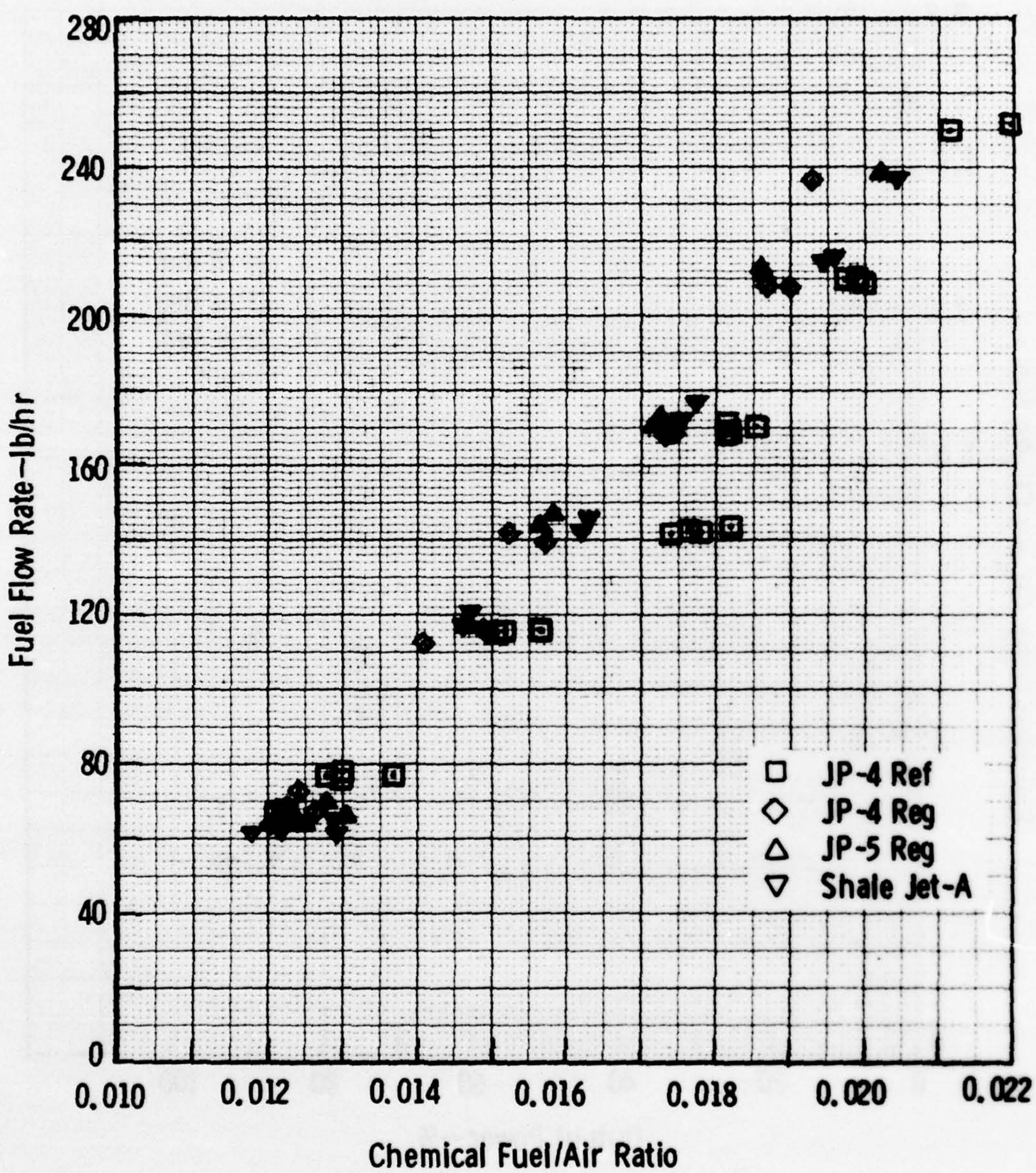

Figure 186. Prechamber Liner Multiple Fuels Engine Test, Fuel Flow Rates at Fuel-to-Air Ratios.

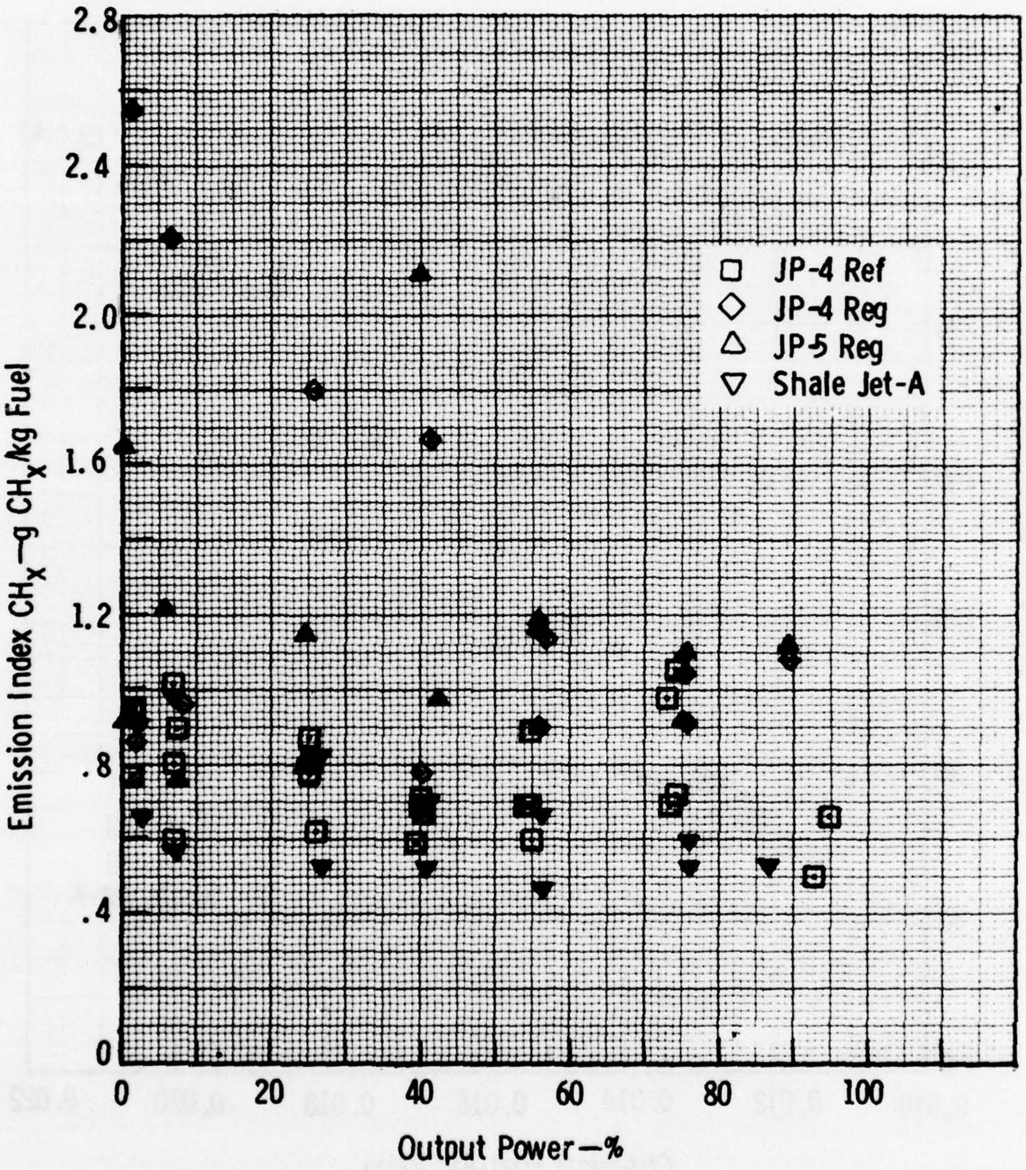

Figure 187. Prechamber Liner Multiple Fuels Engine Test, Unburned Hydrocarbon Emissions.

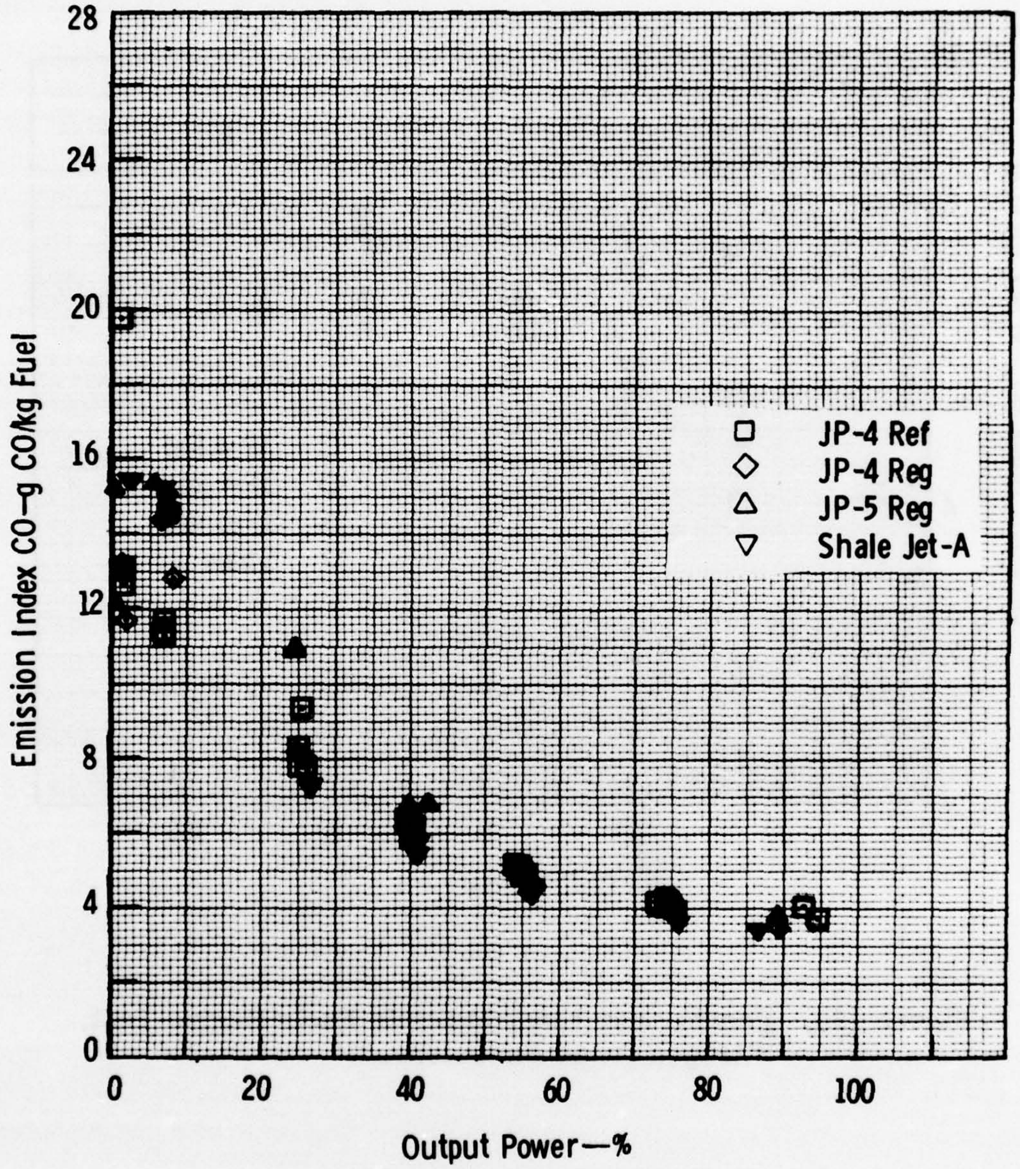

Figure 188. Prechamber Liner Multiple Fuels Engine Test, Carbon Monoxide Emissions.

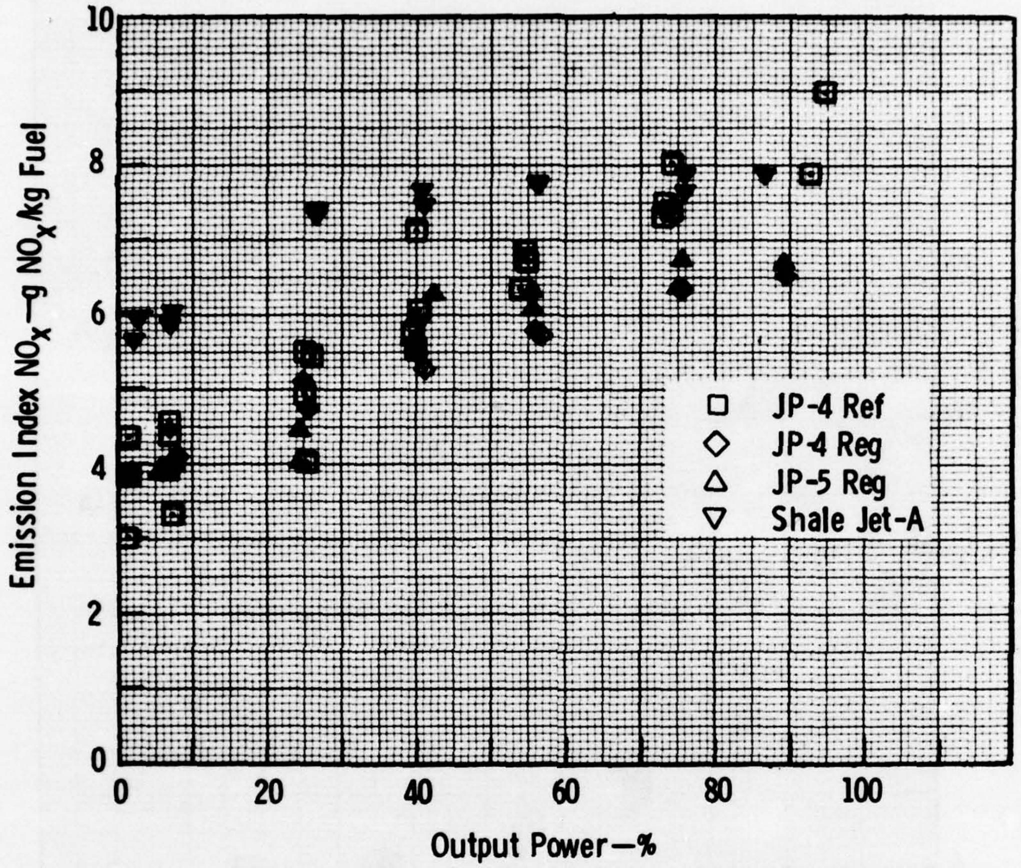

Figure 189. Prechamber Liner Multiple Fuels Engine Test, Nitrogen Oxide Emissions.

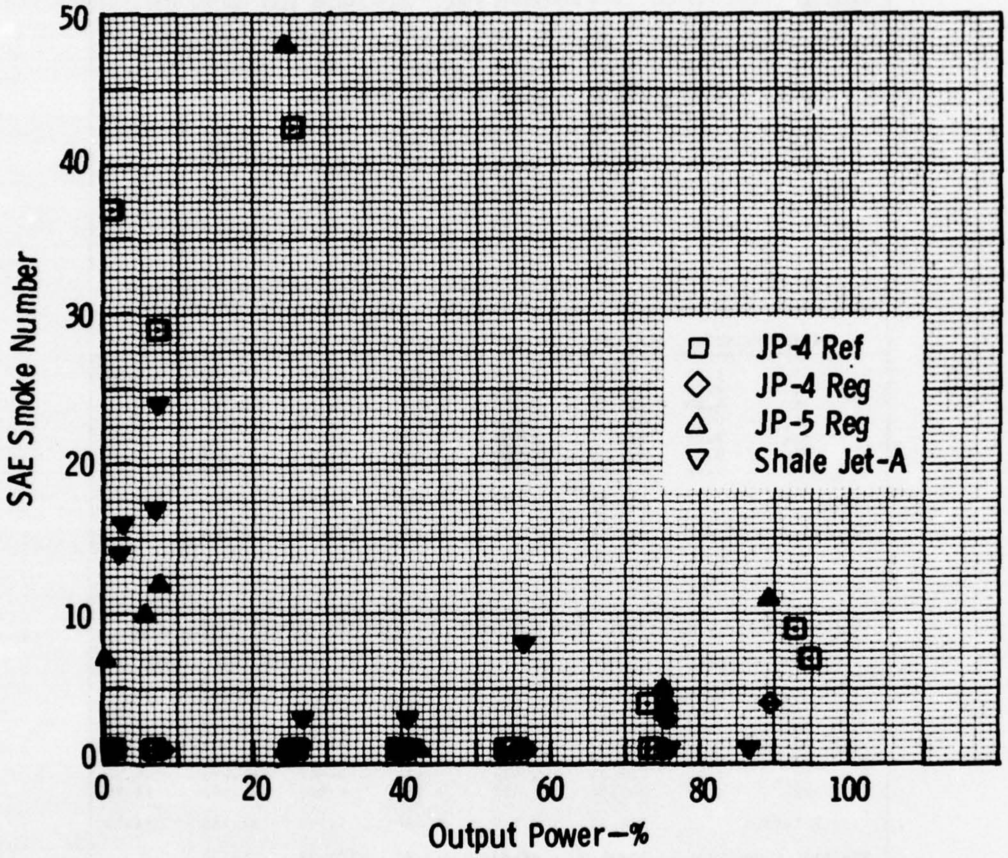

Figure 190. Prechamber Liner Multiple Fuels Engine Test, Exhaust Smoke.

TABLE 101. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS COMPARISON OF PRECHAMBER LINER OPERATING ON DIFFERENT FUELS.

BASELINE LINER, 6871486, JP-4 REFERENCE FUEL, JULY ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	65.00	18.717	145.267	2.320	166.304	11.00
6.	0.15	69.00	17.713	111.199	2.405	131.317	13.50
25.	0.00	113.00	3.621	47.429	3.184	54.234	27.00
40.	0.15	139.00	1.931	29.907	3.815	35.653	33.80
55.	0.45	166.00	1.497	19.305	4.273	25.075	38.50
75.	0.20	204.00	1.138	10.745	4.942	16.825	42.80
100.	0.05	259.00	0.849	5.391	5.977	12.217	46.10
CYCLE TOTALS		159.65	2.461	23.331	4.401	30.193	46.10
PERCENT OF BASELINE		100.00	100.00	100.00	100.00	100.00	

PRECHAMBER LINER, EX-119087, JP-4 REGULAR FUEL, JULY ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	65.50	0.908	15.040	3.852	19.800	1.00
6.	0.15	70.00	0.886	13.758	3.945	18.589	1.00
25.	0.00	115.00	0.838	8.131	4.940	13.909	1.00
40.	0.15	140.00	0.848	5.823	5.494	12.165	1.00
55.	0.45	168.00	0.881	4.588	5.898	11.367	1.00
75.	0.20	207.00	0.984	3.784	6.302	11.070	2.30
100.	0.05	260.00	1.194	3.399	6.700	11.293	7.60
CYCLE TOTALS		161.50	0.929	5.043	5.887	11.858	7.60
PERCENT OF BASELINE		101.16	37.74	21.62	133.75	39.28	

PRECHAMBER LINER, EX-119087, JP-5 REGULAR FUEL, JULY ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	64.20	0.920	15.440	3.887	20.247	10.00
6.	0.15	69.00	0.918	14.752	3.808	19.476	6.50
25.	0.00	118.50	0.935	11.067	4.467	16.469	1.00
40.	0.15	144.00	0.978	7.106	5.938	14.022	1.00
55.	0.45	173.00	1.024	5.078	6.255	12.357	1.00
75.	0.20	212.00	1.090	4.120	6.467	11.677	4.80
100.	0.05	261.00	1.152	3.520	6.848	11.520	18.00
CYCLE TOTALS		165.25	1.038	5.580	6.162	12.780	18.00
PERCENT OF BASELINE		103.51	42.20	23.92	139.99	42.33	

PRECHAMBER LINER, EX-119087, SHALE JP-5/JET-A FUEL, JULY ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	61.00	0.636	16.619	5.526	22.781	16.00
6.	0.15	63.50	0.607	13.469	6.103	20.179	11.00
25.	0.00	118.00	0.544	7.633	7.236	15.413	2.20
40.	0.15	143.00	0.523	5.542	7.642	13.707	1.00
55.	0.45	171.00	0.523	4.423	7.816	12.762	1.00
75.	0.20	212.50	0.529	3.654	7.901	12.084	1.00
100.	0.05	269.00	0.548	3.234	7.856	11.638	1.00
CYCLE TOTALS		163.87	0.531	4.798	7.719	13.049	16.00
PERCENT OF BASELINE		102.65	21.60	20.57	175.38	43.22	

Output horsepower is plotted against mechanical fuel-air ratio in Figure 177 and shows very good repeatability for all power levels up through 75% power (315 hp). The engine was limited to 1490°F interstage turbine temperature, which is takeoff (100% power) with the baseline combustor. Therefore, due to combustor exhaust temperature pattern shifts and lack of uniformity, 100% power (420 hp) was not run. Output power, hp and percent, are plotted versus the chemical fuel-air ratio in Figures 179 and 180. The chemical fuel-air ratios varied considerably more than the mechanical values. This can be seen in Figure 180, which is a comparison of chemical and mechanical fuel-air ratios. This comparison shows that the chemical fuel-air ratios derived from the exhaust gas analysis consistently gave higher values than the mechanical fuel-air ratios.

Plots of the data points for hydrocarbon, carbon monoxide, and nitrogen oxides as functions of the chemical fuel-air ratio are presented in Figures 181 through 183. For the hydrocarbon data, which seemed to be the most sensitive to fuel types, the oil-shale-derived fuel produced the lowest exhaust hydrocarbons, while the JP-5 produced the highest. All fuels gave concentrations below 30-40 ppm. The JP-4 regular fuel data in Figure 181 are erroneous because of the sample line to the FID ingested raw fuel during an abortive fire-up. As can be noted from the data summary in Table 97, hydrocarbon concentrations steadily decreased with reading number and clock time. The carbon monoxide concentrations in Figure 182 showed close agreement among fuel types, but the nitrogen oxides plot in Figure 183 showed that a significant portion of the fuel-bound nitrogen in the oil shale fuel was converted to NO_x in the combustion process, resulting in consistently higher concentrations than from the other fuels. From a special fuel analysis test, JP-4 reference fuel was .006% nitrogen by weight, while the oil shale fuel was .100% nitrogen by weight or had about 17 times the nitrogen.

Exhaust emissions from the JP-4 regular, JP-5 regular, and shale JP-5/Jet-A fuel tests were time-weight averaged over the LOH duty cycle and then compared with the baseline recalibration engine data. As seen in Table 101, the three fuels showed little effects on the quantities of exhaust emissions produced with the exception of the nitrogen emissions from the shale-derived fuel. These NO_x emissions were noticeably higher, again probably caused by the fuel-bound nitrogen. From these results, the total emissions were reduced 57-61%, and CH_x and CO concentrations were reduced 60-80% from the baseline liner. Only the high NO_x levels kept the prechamber combustor from achieving all of its emissions goals.

A plot of smoke number as a function of chemical fuel-air ratio is given in Figure 184. If the four smoke numbers above 25 are ignored (because of the improper seating of the flame during the JP-4 reference testing and the JP-5 testing at low power levels), the exhaust smoke was well below the visible limit for all of the fuels. Combustion efficiency is shown in Figure 185, and fuel flow rate is shown in Figure 186.

Emission index plots of hydrocarbon, carbon monoxide, and nitrogen oxides were presented in Figures 187 through 189 against percent output power. Exhaust smoke was shown in Figure 190.

The photographs in Figures 191 through 194 show the condition of the prechamber combustor liner after completion of the multiple fuels testing. Figures 191 through 193 show the lateral surface of the liner. It can be seen that, with the exception of the cylindrical surface in the region of the intermediate and dilution holes, none of the metal showed any signs of excessive heating. In Figure 194 the external view of the swirler shows that the vanes suffered some mechanical damage, probably caused by liner alignment prior to the insertion of the fuel nozzle and/or spark igniter.

The fuel nozzle showed signs of carbon buildup during the engine testing. Figure 195 is a photograph of the fuel nozzle, EX-115870C, after the oil shale JP-5/Jet-A fuel emissions test. It is not known how much of this buildup was caused by the shale oil fuel by itself. Figure 196 shows the carbon buildup of JP-4 fuel deposits on airblast nozzle EX-114779 after a two-hour test.

For all of the emissions running, the airblast fuel injector was operated only on the main fuel system (no pilot). Engine start-up was generally accomplished on main only. However, JP-5 fuel would not allow main start-up; so, for this fuel and for any other difficult starting times, the pilot side of the nozzle was connected through a shutoff valve so that once the engine reached idle the pilot could be shut off. The only other problem was not achieving 100% power, which was probably caused by a poor liner exhaust temperature pattern. Thus, when the interturbine temperature reached 1490°F, the normal 100% power temperature, this constituted the maximum performance point for the run. Early running with the liner achieved very nearly 100% power, but the distortion to the metal in the dilution and intermediate air addition region was probably responsible for the deterioration of the liner exhaust temperature pattern and thus the higher than normal interturbine temperature.

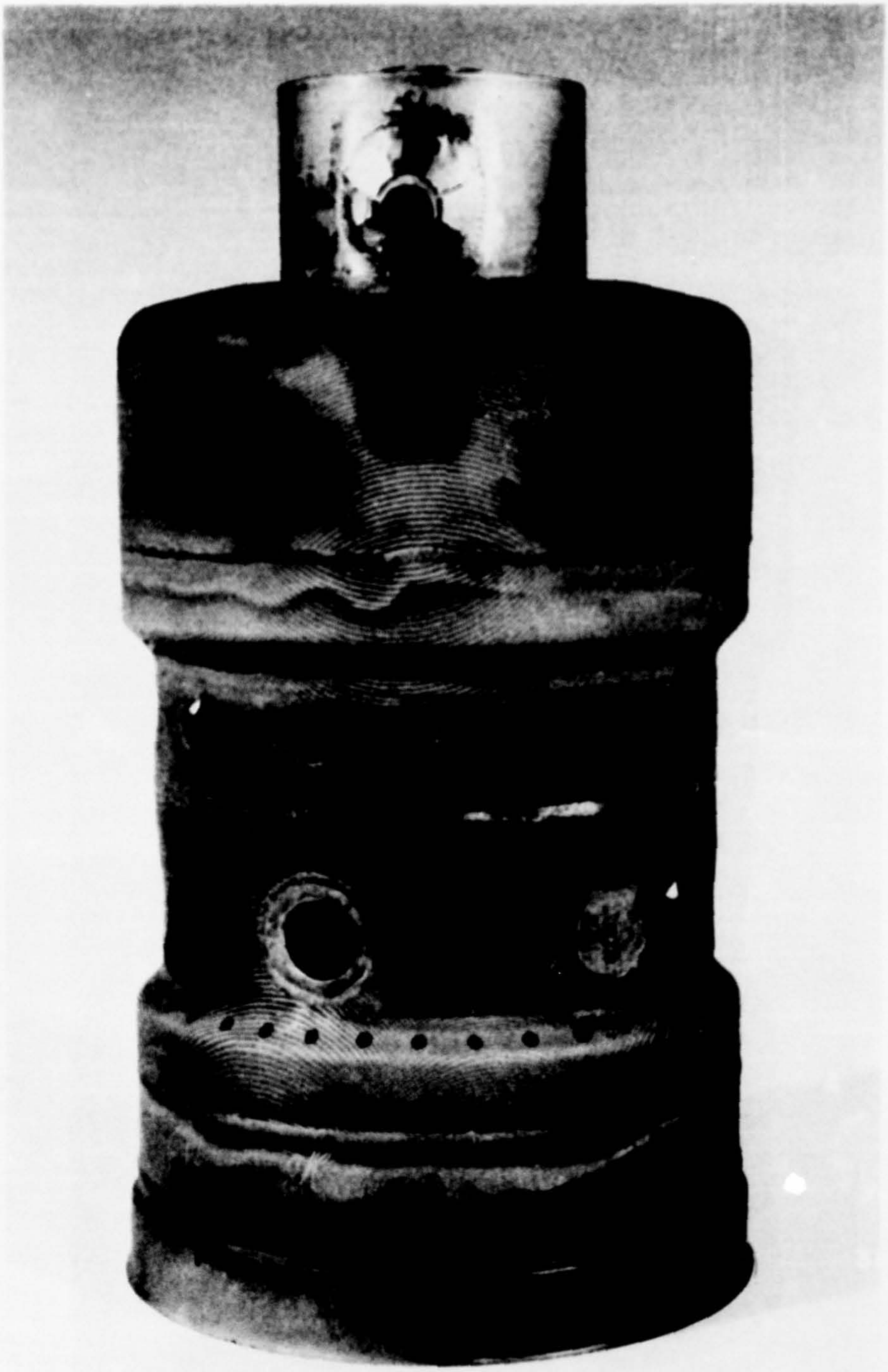

Figure 191. Prechamber Liner No. 17 After Multiple Fuels Test, External 75°-195° Rotation.

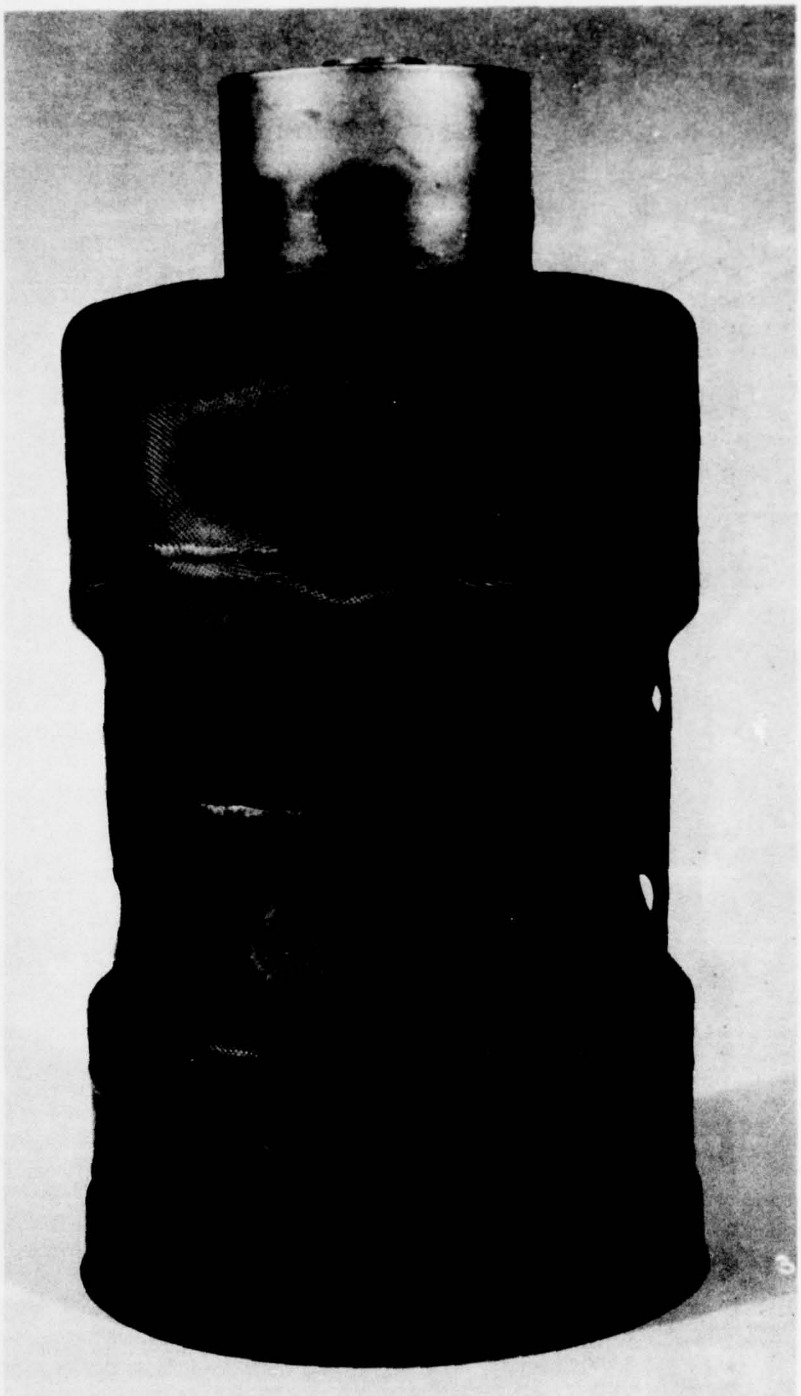

Figure 192. Prechamber Liner No. 17 After Multiple Fuels Test, External 180°-330° Rotation.

Figure 193. Prechamber Liner No. 17 Multiple Fuels Test, External 300°-90° Rotation.

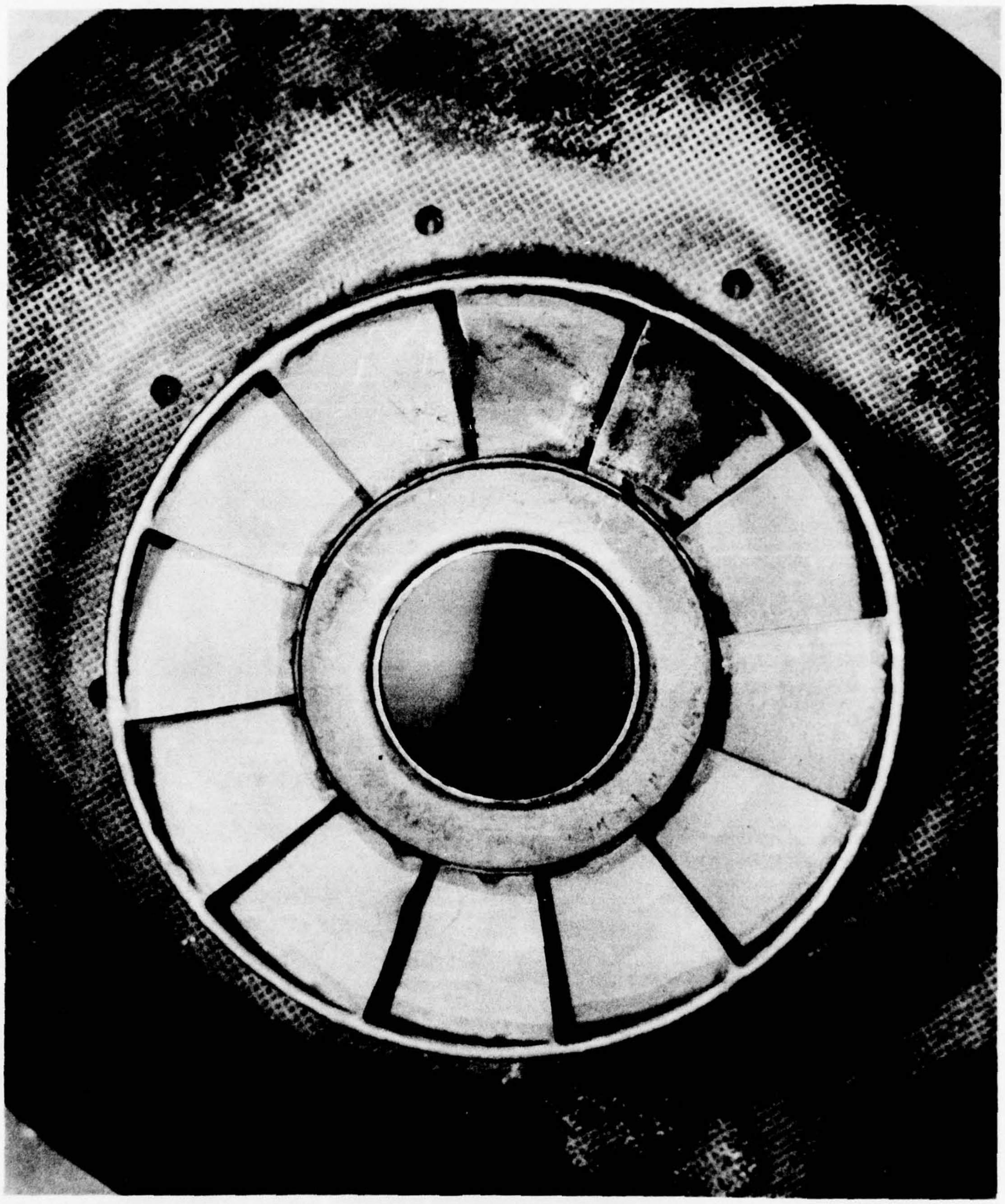

Figure 194. Prechamber Liner No. 17 After Multiple Fuels Test, Prechamber Swirler.

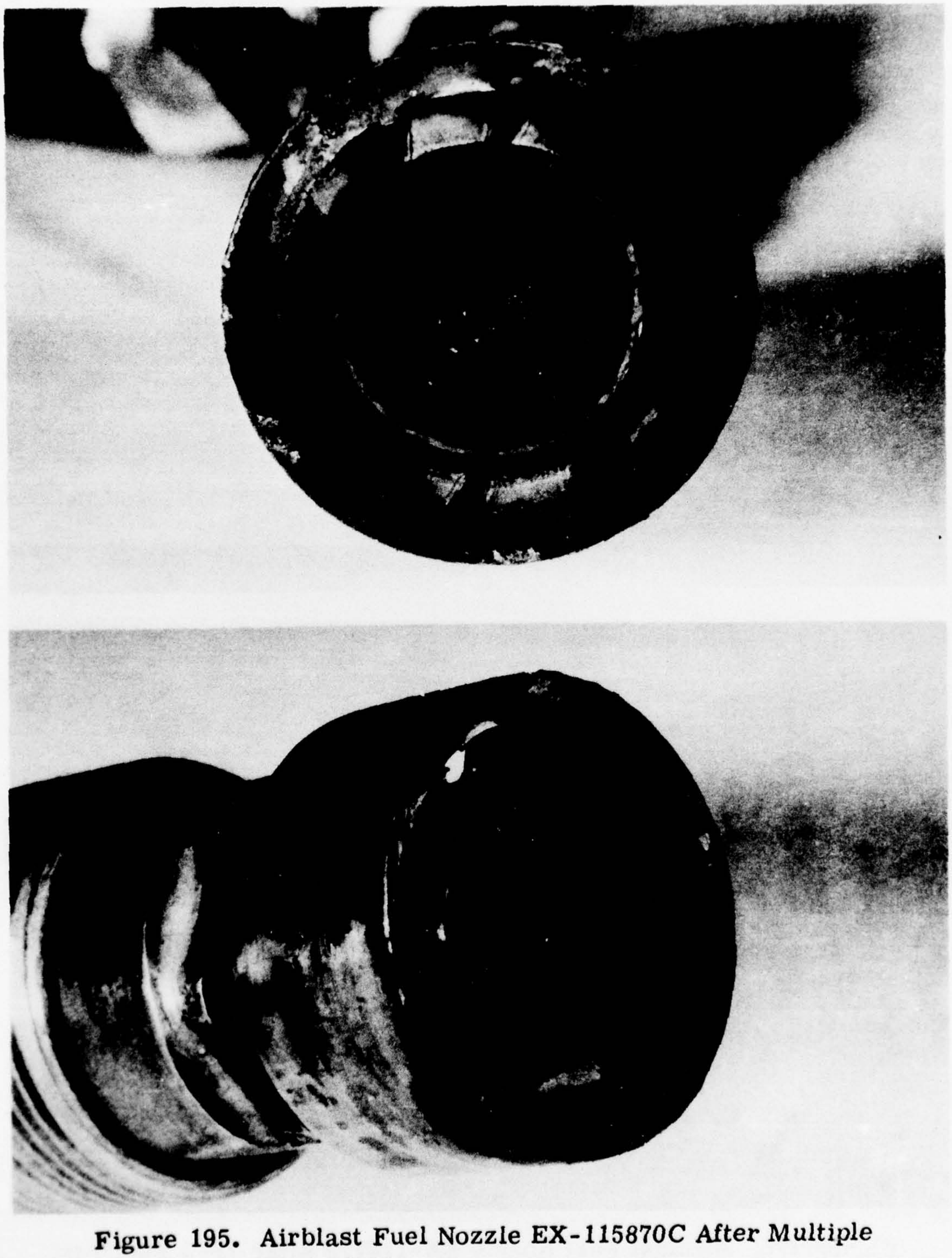

Figure 195. Airblast Fuel Nozzle EX-115870C After Multiple Fuels Test.

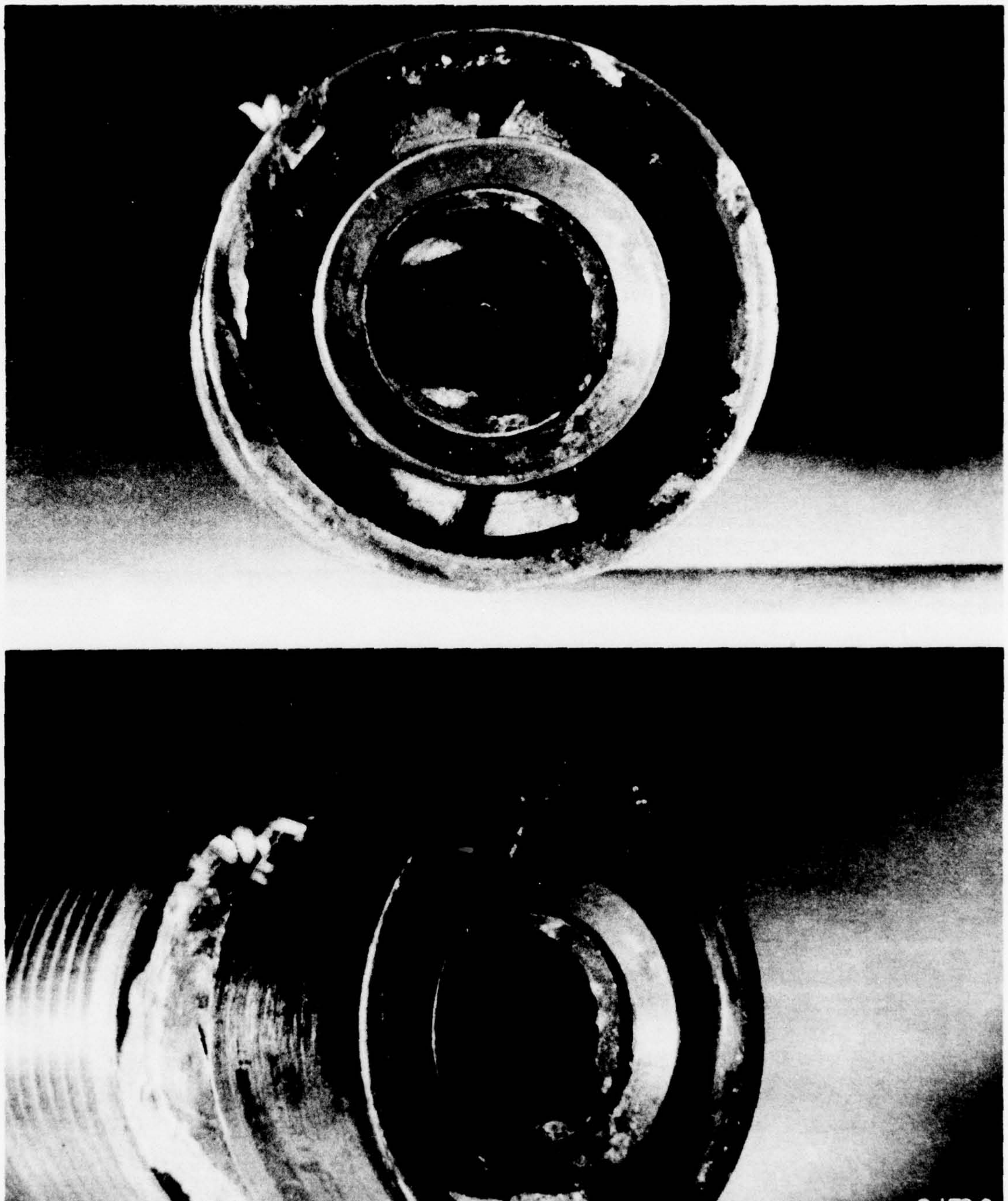

Figure 196. Airblast Fuel Nozzle EX-114779 After JP-4 Fuel Test.

MODIFIED CONVENTIONAL COMBUSTOR

The low emission modified conventional combustor system delivered to the Model 250-C20B engine for initial engine testing is itemized in Table 102. This combustion liner (modified conventional No. 11) was identical to the final rig development combustor with the exception of the circumferential position of the four 0.625-inch-diameter high-power dilution holes. On liner No. 11 these dilution holes were located ±45° to the horizontal plane whereas these holes were located ±30° on liner No. 10 or ±60° on liner No. 8. The combustor outer case, liner, and combustor

TABLE 102. LOW EMISSIONS MODIFIED CONVENTIONAL COMBUSTOR PARTS LIST.

Part Name	Part Number
Outer Case	EX-115859
Liner	EX-118916
Igniter	6843984
Fuel System	
Nozzle	EX-115870C
Pressure Relief Valve	SS-4CPA2-150
Variable Geometry Parts	
Clevis Pins (2)	EX-118928
Clevis (2)	EX-118929
Actuator Rods (2)	EX-118930
Mounting Blocks (2)	None
Support Plate	None
Air Cylinders (2)	042-D
Compression Fittings (2)	T-128671-3
Male Connector (2)	810-1-12-316
Reducer (2)	400-R-8-316

assembly are presented in Figures 197 through 203. The fuel nozzle used with the modified conventional liner was the same airblast device used with the prechamber. However, unlike in the prechamber tests, the pilot fuel system was used extensively. With a pilot tip flow number of 4.0, the pilot fuel line was connected directly to the engine fuel supply line. To force the idle fuel flow to be from the pilot only, for low CO and CH_x emissions, a pressure relief valve with a cracking pressure of 300-320 psi was inserted into the main fuel supply line. With this system, the fuel for idle conditions was supplied through the pilot, and the fuel for higher power operating conditions was supplied essentially through the secondary airblast system.

The two-position, rotating-band, dilution variable geometry was actuated by two rods, which were connected through mounting blocks to two air cylinders that were supported by the actuator-rod case tubes fixed to the combustor outer case. The air cylinder actuation was adjusted so that one cylinder would be actuated to pull and the other push its attached rod and thus rotate the liner dilution band from one position to the next. The actuation of the geometry was accomplished manually by the operator so that at midpower, the performance of both positions could be investigated.

Exhaust Temperature Profile

The first engine testing was an initial shakedown of the liner, fuel nozzle, and dilution variable geometry hardware. It was followed by a combustor exhaust-temperature profile run with the forty-eight thermocouple instrumentation ring installed. The poor temperature pattern measured from the first liner engine tested, No. 11, is shown in Figure 204. These results led to a succession of three more liner configurations before the emissions measurements were conducted. The specific liner temperature patterns measured are shown in Figures 205 through 207. Changes to the modified conventional combustors were restricted to the hole pattern of the high-power geometry setting.

To conserve instrumentation thermocouples, maximum temperatures were held to the 2150°-2200°F range, which limited the tests to a 75% power maximum. A summary of the temperature profile data sets is given in Table 103.

The final liner configuration used for the emissions testing was modified conventional liner No. 12. The high-power setting dilution hole pattern in this liner was four holes of .625 inch in diameter and equally spaced

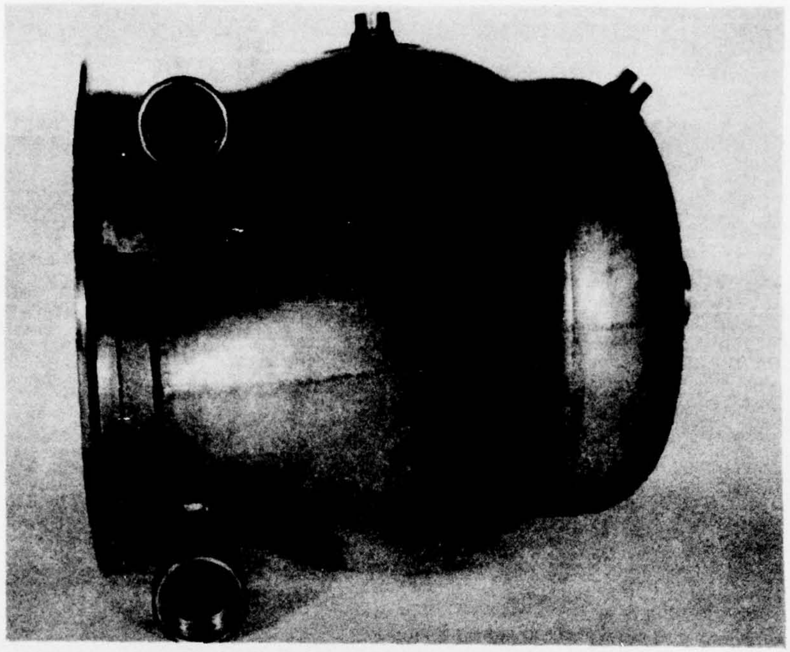

Figure 197. Modified Conventional Outer Combustion Case EX-115859, External View.

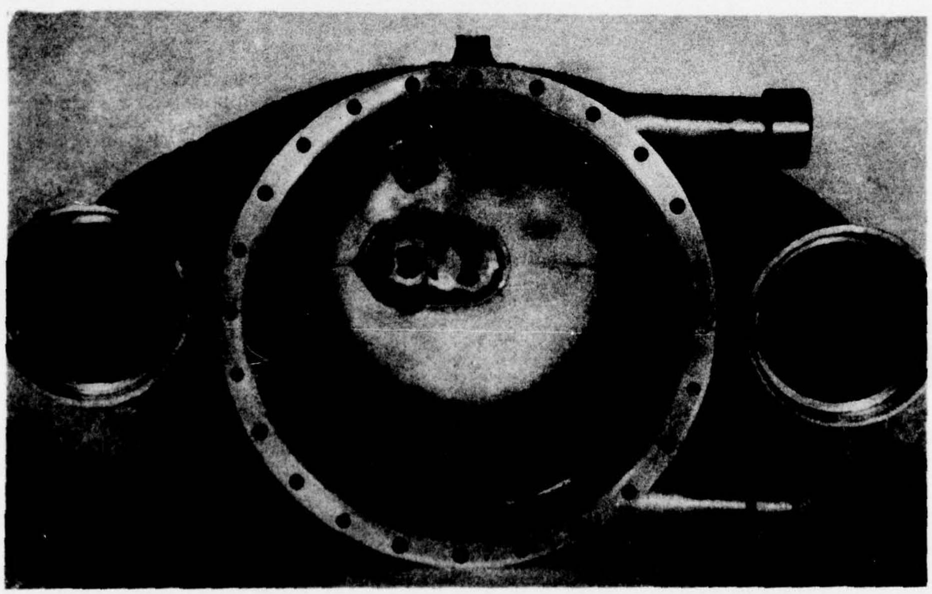

Figure 198. Modified Conventional Outer Combustion Case EX-115859, Internal View.

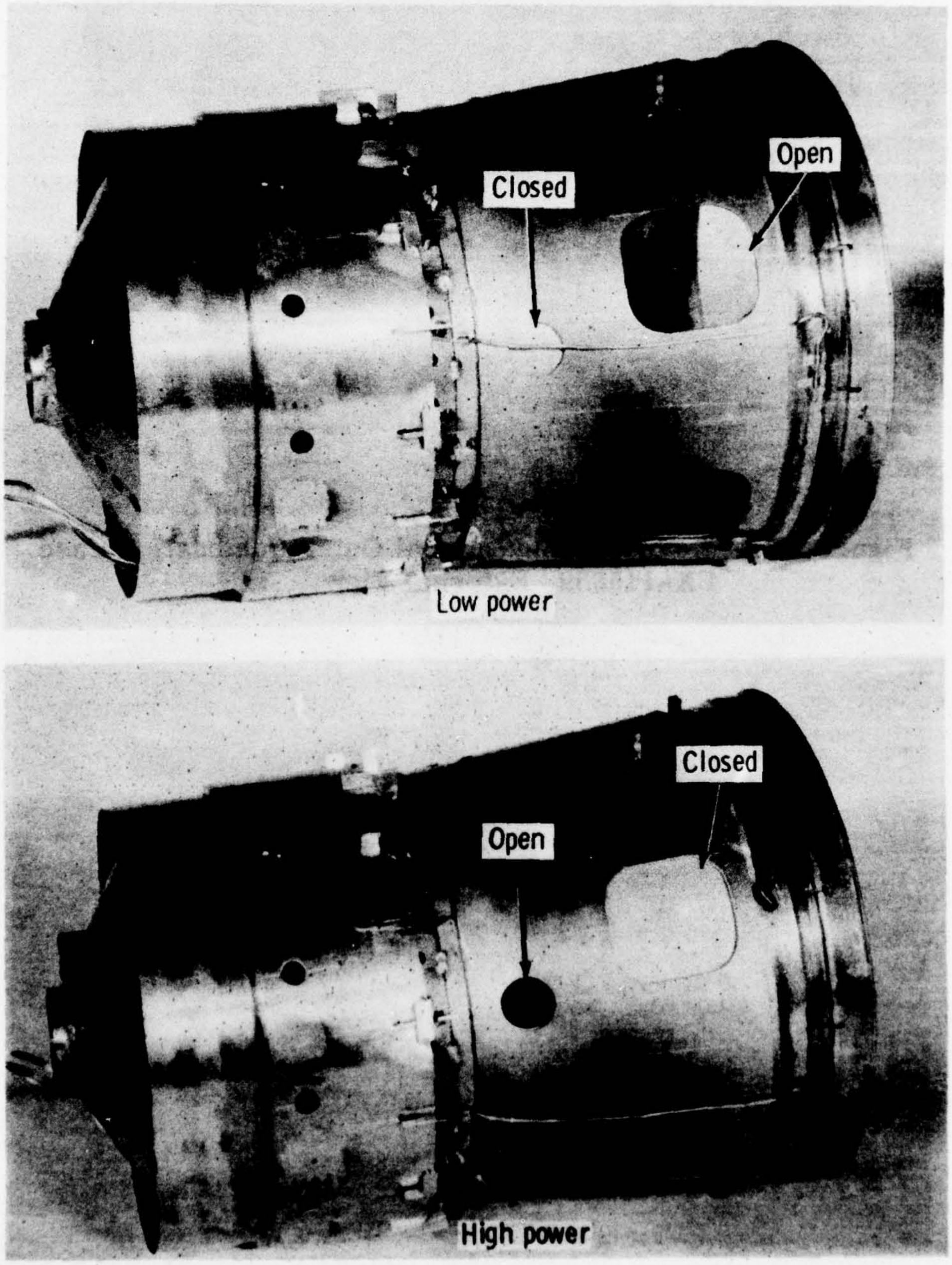

Figure. 199. Modified Conventional Liner No. 11, External Views Showing Low Power (Top) and High Power (Bottom) Geometry Settings.

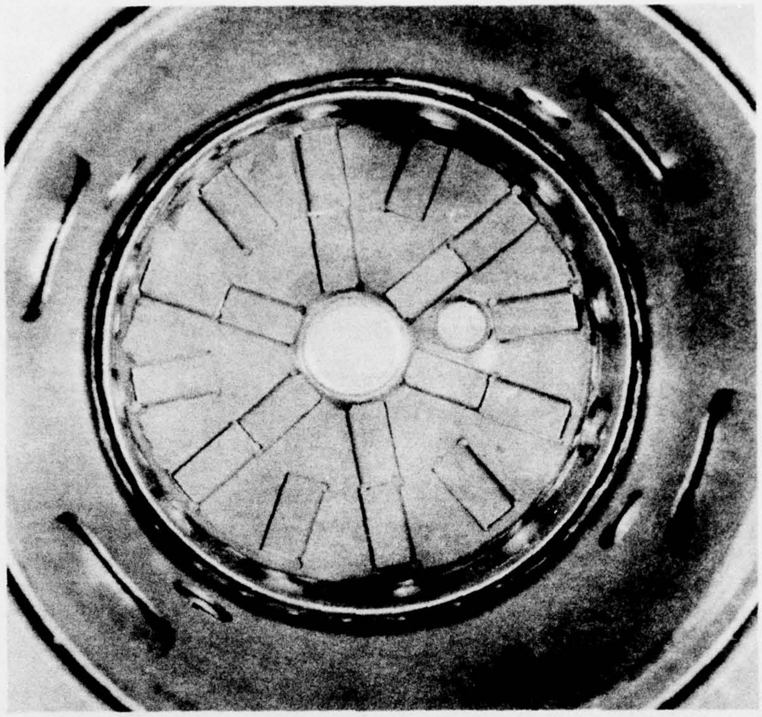

Figure 200. Modified Conventional Liner No. 11, Internal View.

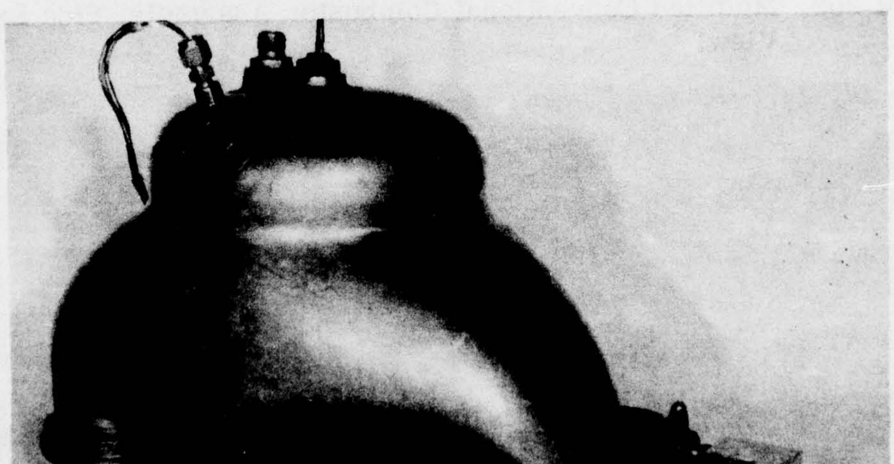

Figure 201. Modified Conventional Combustor Assembly, Three-Quarter External View.

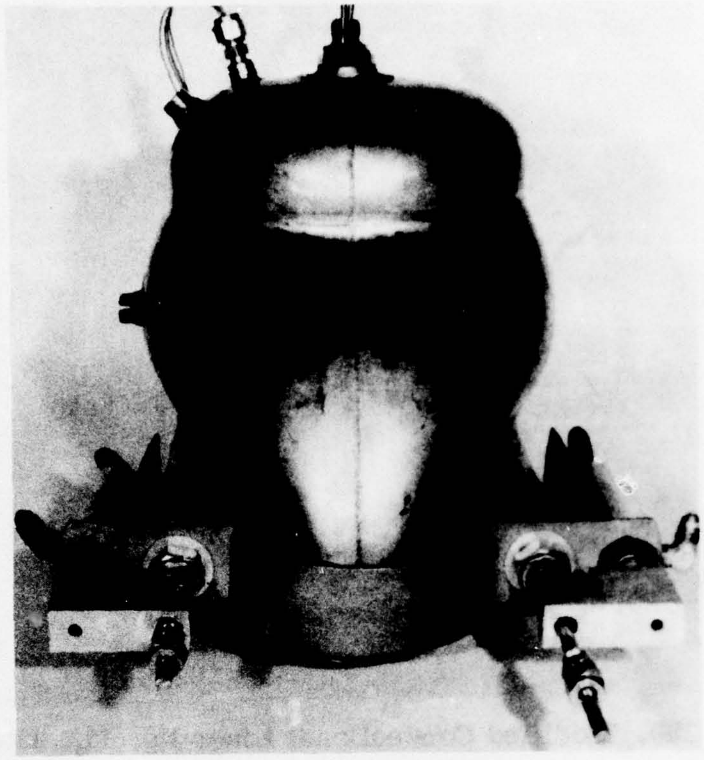

Figure 202. Modified Conventional Combustor Assembly, Side External View.

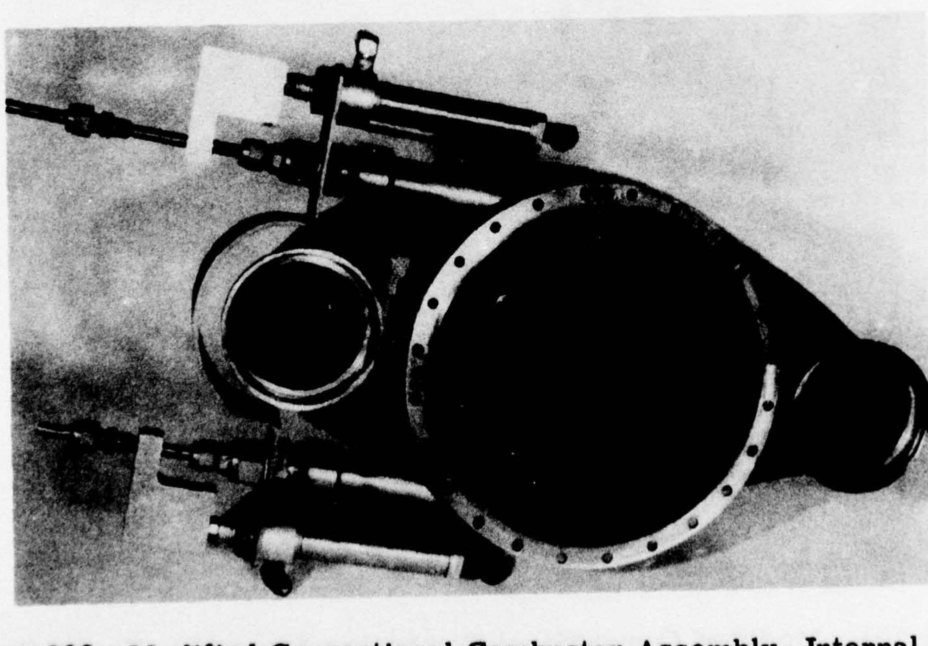

Figure 203. Modified Conventional Combustor Assembly, Internal View.

LOW-EMISSION MODIFIED CONVENTIONAL COMBUSTOR OPERATING AT 40% POWER TURB TEMP
TEST DATE = 3-31-75 READING NUMBER = 213 INLET TEMP = 432.
ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 1125.
OUTER CASE NUMBER/NAME = EX-115859 / VARIABLE GEOMETRY
LINER NUMBER/NAME = EX-118916 / MOD. CONVENTIONAL

	* * * * * A N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1531.0	1618.3	1624.6	1588.5
MAXIMUM TEMPERATURE	1860.0	2060.0	2210.0	2210.0
(AVG-INLET) TEMP	1099.0	1186.3	1192.6	1156.5
(MAX-AVG) TEMP	329.0	441.7	585.4	621.5
MAX TEMP/AVG TEMP	1.2149	1.2729	1.3603	1.3912
(MAX-AVG)/(AVG-IN)	0.2994	0.3723	0.4908	0.5373
(AVG-AVG TOTAL)	-57.5	29.8	36.1	
(TIP-HUB) AVG TEMP				93.6
(AVG TOTAL-TOT)				463.5

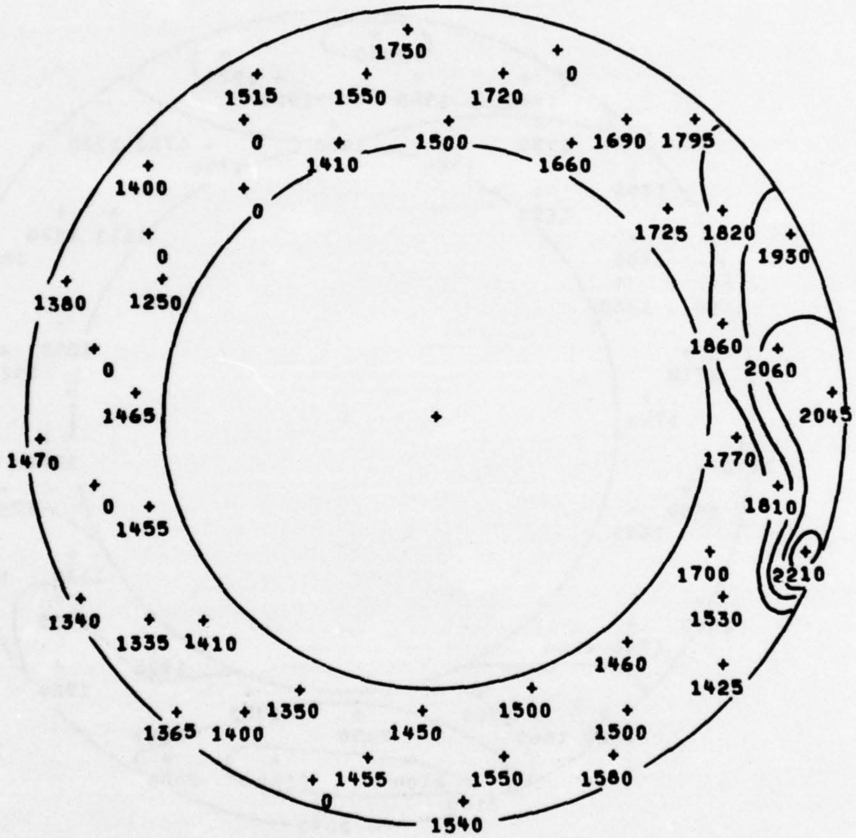

Figure 204. Modified Conventional Liner No. 11 Exhaust Temperatures at 40% Engine Power.

LOW-EMISSION MODIFIED CONVENTIONAL COMBUSTOR OPERATING AT 75% POWER TURB TEMP

TEST DATE = 4- 1-75 READING NUMBER = 219 INLET TEMP = 536.

ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 1323.

OUTER CASE NUMBER/NAME = EX-115859 / VARIABLE GEOMETRY

LINER NUMBER/NAME = EX-116292 / MOD. CONVENTIONAL

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1777.8	1811.2	1831.9	1807.0
MAXIMUM TEMPERATURE	2050.0	2140.0	2100.0	2140.0
(AVG-INLET) TEMP	1241.8	1275.2	1295.9	1271.0
(MAX-AVG) TEMP	272.2	328.7	268.1	333.0
MAX TEMP/AVG TEMP	1.1531	1.1815	1.1464	1.1843
(MAX-AVG)/(AVG-IN)	0.2192	0.2578	0.2069	0.2620
(AVG-AVG TOTAL)	-29.2	4.3	24.9	
(TIP-HUB) AVG TEMP				54.1
(AVG TOTAL-TOT)				484.0

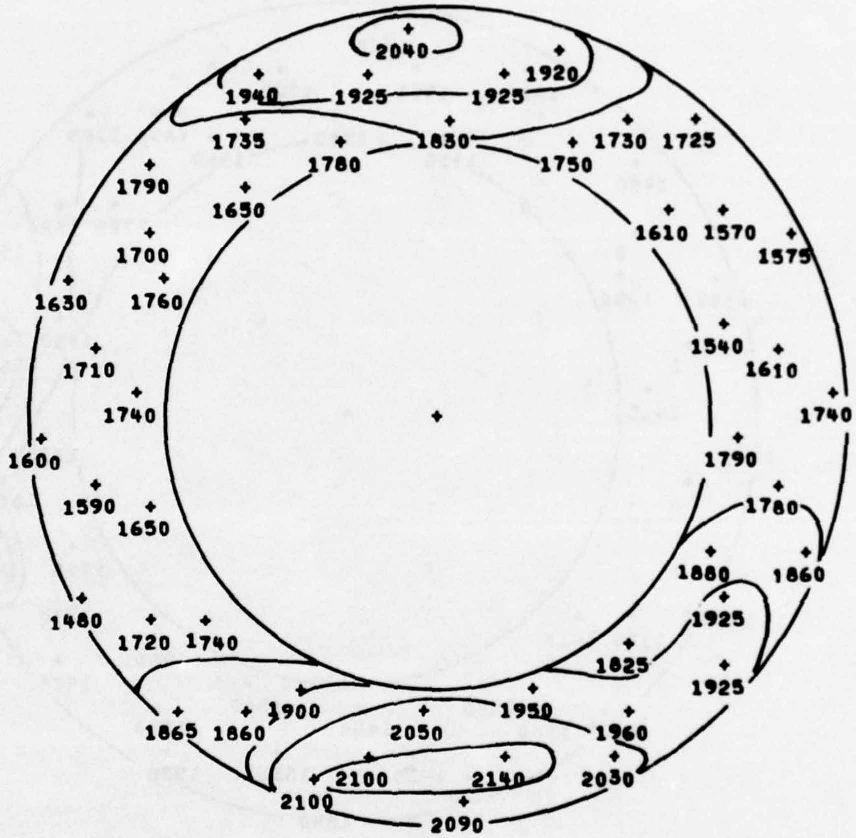

Figure 205. Modified Conventional Liner No. 10 Exhaust Temperatures at 75% Engine Power.

LOW-EMISSION MODIFIED CONVENTIONAL COMBUSTOR OPERATING AT 75% POWER TURB TEMP
TEST DATE = 4- 7-75 READING NUMBER = 227 INLET TEMP = 530.
ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 1290.
OUTER CASE NUMBER/NAME = EX-115859 / VARIABLE GEOMETRY
LINER NUMBER/NAME = EX-119067 / MOD. CONVENTIONAL

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1767.5	1769.1	1789.4	1775.3
MAXIMUM TEMPERATURE	2030.0	2050.0	2150.0	2150.0
(AVG-INLET) TEMP	1237.5	1239.1	1259.4	1245.3
(MAX-AVG) TEMP	262.5	280.9	360.6	374.7
MAX TEMP/AVG TEMP	1.1485	1.1588	1.2015	1.2111
(MAX-AVG)/(AVG-IN)	0.2121	0.2267	0.2864	0.3009
(AVG-AVG TOTAL)	-7.8	-6.3	14.1	
(TIP-HUB) AVG TEMP				21.9
(AVG TOTAL-TOT)				485.3

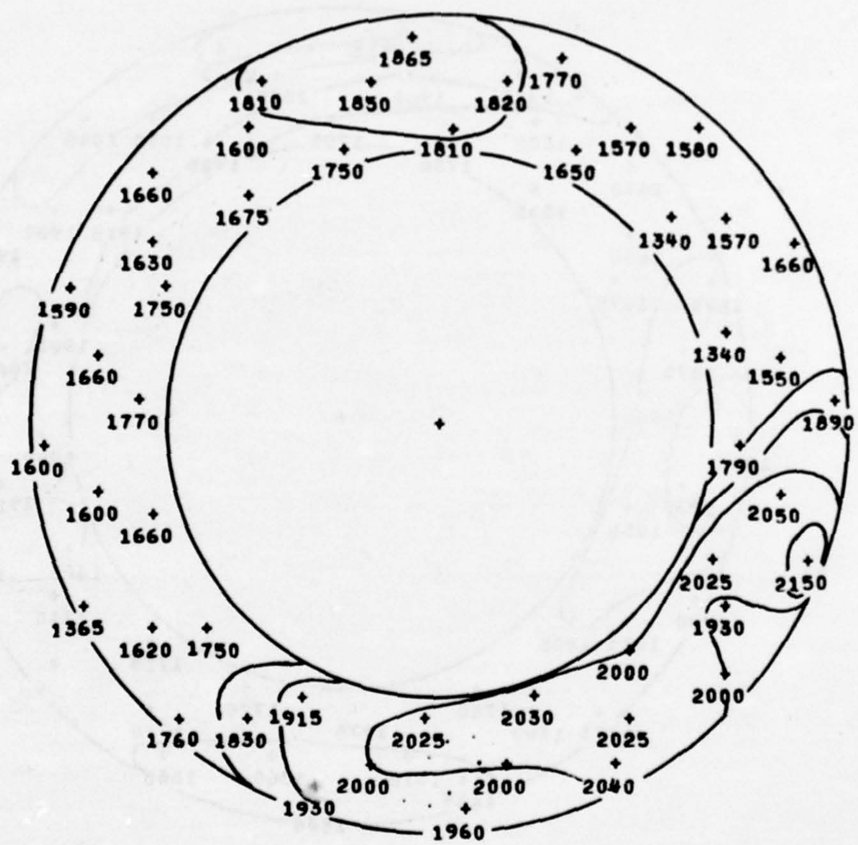

Figure 206. Modified Conventional Liner No. 13 Exhaust Temperatures at 75% Engine Power.

LOW-EMISSION MODIFIED CONVENTIONAL COMBUSTOR OPERATING AT 75% POWER TURB TEMP
TEST DATE = 4- 8-75 READING NUMBER = 231 INLET TEMP = 536.
ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 1320.
OUTER CASE NUMBER/NAME = EX-115859 / VARIABLE GEOMETRY
LINER NUMBER/NAME = EX-119016 / MOD. CONVENTIONAL

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1800.0	1847.8	1905.7	1850.0
MAXIMUM TEMPERATURE	1980.0	2060.0	2135.0	2135.0
(AVG-INLET) TEMP	1264.0	1311.8	1369.7	1314.0
(MAX-AVG) TEMP	180.0	212.2	229.3	285.0
MAX TEMP/AVG TEMP	1.1000	1.1148	1.1203	1.1541
(MAX-AVG)/(AVG-IN)	0.1424	0.1618	0.1674	0.2169
(AVG-AVG TOTAL)	-50.0	-2.2	55.7	
(TIP-HUB) AVG TEMP				105.7
(AVG TOTAL-TOT)				530.0

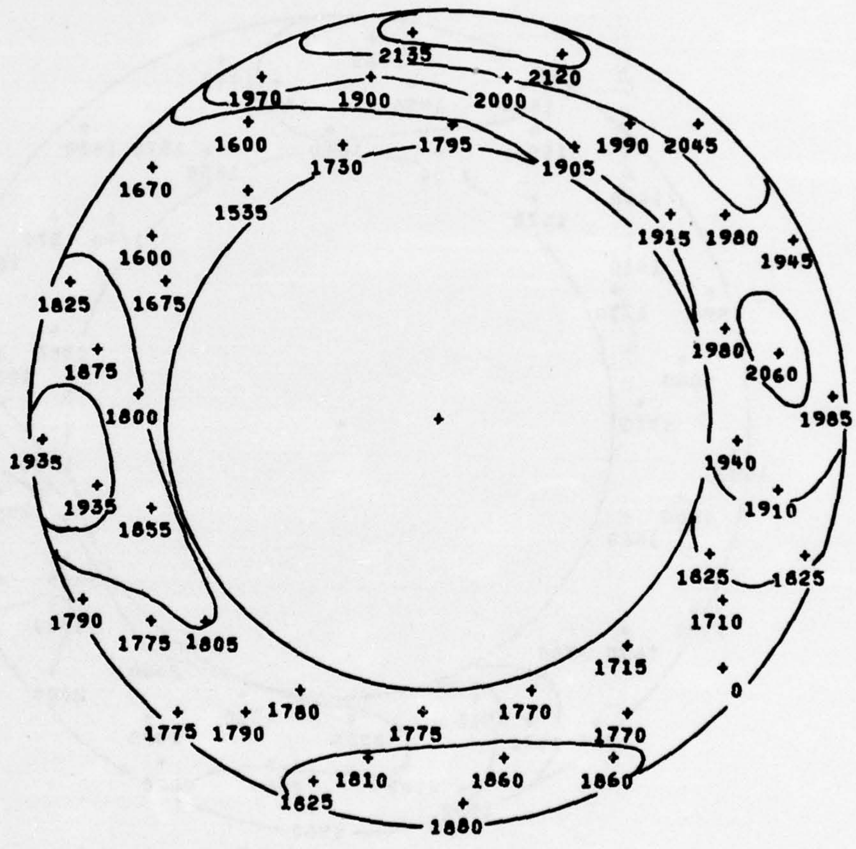

Figure 207. Modified Conventional Liner No. 12 Exhaust Temperatures at 75% Engine Power.

TABLE 103. COMBUSTOR OUTLET TEMPERATURE PROFILE PARAMETERS FOR MODIFIED CONVENTIONAL LINER OPERATING ON MODEL 250-C20B ENGINE.

Combustion Liner		Approximate Output Horsepower (%)					
		40		55		75	
Series No.	P/N	Tm/Ta	P.F.	Tm/Ta	P.F.	Tm/Ta	P.F.
10.	EX-116292	1.168	.232	1.177	.246	1.184	.262
11.	EX-118916	1.391	.537	-	-	-	-
12.	EX-119066	-	-	1.143	.197	1.154	.217
13.	EX-119067	1.148	.205	1.135	.187	1.211	.301

±45° on either side of the horizontal centerline, plus one hole at 270° (looking downstream) in the same axial plane at .500 inch in diameter. The pattern factor values in Table 103 used baseline engine values for the combustor inlet temperature, T_3, since the low-emission liners measured this temperature with a thermocouple through the outer case dome. At this location, the modified conventional T_3 measured values were 10° to 30° lower than a similarly placed T_3 thermocouple read in the baseline combustor system. The reason for the decrease was the presence of the convection cooling shell, which surrounded the reaction zone on the modified conventional liner. This insulated the air flowing to the liner dome from the hot metal, thus resulting in slightly cooler temperatures.

As seen from Table 103, modified conventional liner No. 12, which has a nonsymmetric five-hole liner pattern for high power operation, produced the best pattern at approximately 75% output power conditions.

Exhaust Emissions

Exhaust emissions measurements were recorded at the LOH duty cycle steady-state operating conditions on the modified conventional liner No. 12. Data were taken for each low-emission combustor in both ascending and descending power sequences on two separate runs. The fuel nozzle system was connected to fuel only the pilot nozzle at both idle conditions. To accomplish this, a pressure relief valve with approximately 320 psi cracking pressure was connected in series to the airblast main fuel line, downstream from the "T" fitting that branches from the input line to the two separate fuel tubes for the nozzles. At fuel rates higher than idle,

the pressure relief valve opened and the additional fuel was added through the main airblast system. Thus, above idle conditions, the pilot fuel rate was more than 70 lb/hr. The balance was used for achieving the required operating point and was supplied by the airblast main fuel nozzle. The estimated performance of the fuel nozzle is presented in Figure 208, showing the mode of operation during engine testing.

The modified conventional liner had emissions measured at twenty-nine points. The dilution-zone variable geometry was on the low-power setting for ground idle (5 hp), operational idle (25 hp), 25, 40, and 55% power conditions. The geometry was then changed to the high-power setting and data were taken at 55 (repeat), 75, and 100% power. Thus, four data points were taken at both idles, at 25, at 40, and at 75% power, eight data points (two geometry settings) at 55% power, and one data point at 100% power. The first 100% power point revealed a shift in the combustor exit temperature profile, as evidenced by a visible red streak along the bottom of the turbine case. Thus, to assure no additional chance of damage to the engine, the second 100% power point was aborted for this liner.

A summary of the recorded data is presented in Table 104 for the modified conventional liner. Plots of CO, CH_x, and NO_x emission indexes versus percent output power are presented in Figures 209 through 211, and the plot of smoke number versus power is in Figure 212. Each of these plots also compares the modified conventional liner with the baseline liner emissions.

As indicated in Figure 213, good agreement was achieved between chemical and mechanical fuel-air ratios. An analysis of fuel-air ratio agreement between baseline and modified conventional combustors is shown in Table 105. Each combustor gave slightly higher chemical fuel-air ratios, on the average 1.1% for baseline and 1.4% for modified conventional, but all data were within ±10% variation and within the two sigma range of variation, which was less than ±8%. Mechanical fuel-air ratios were very consistent from point to point during the emissions run. Summaries of the baseline and the modified conventional liner mechanical fuel-air ratios are shown in Table 106. In the modified conventional liner table, an "L" means low-power dilution geometry setting and "H" means the high-power setting.

Average emissions at the LOH duty cycle power points were taken from the emissions versus power curves. The concentrations and other data so generated are shown in Table 107. These results were time-weight

TABLE 104. EXHAUST EMISSIONS FROM ENGINE TESTING OF MODIFIED CONVENTIONAL LINER OPERATING ON JP-4 REFERENCE FUEL.

RDG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
258.	16.7	308.0	64.0	2.28	68.8	3.0	0.01138	0.01150	0.990	99.099	26.459	3.148	2.356	3.6	0.9
259.	16.3	207.0	41.5	2.45	79.1	4.0	0.01217	0.01190	1.022	99.436	16.650	1.911	2.153	29.3	7.0
260.	34.0	136.0	23.0	3.07	115.5	7.0	0.01524	0.01470	1.037	99.706	8.759	0.848	3.597	107.3	25.5
261.	44.0	121.0	26.5	3.07	144.5	12.0	0.01521	0.01560	0.975	99.712	7.808	0.979	4.664	168.6	40.1
262.	61.0	147.0	20.5	3.57	172.4	19.0	0.01773	0.01640	1.081	99.728	8.158	0.652	5.561	229.6	54.7
263.	46.0	113.0	21.5	3.49	169.4	9.0	0.01731	0.01620	1.069	99.770	6.421	0.700	4.293	229.0	54.5
264.	56.0	82.0	22.5	3.75	208.3	11.0	0.01861	0.01830	1.017	99.817	4.341	0.682	4.869	310.2	73.9
265.	81.0	87.5	14.0	4.08	258.8	14.0	0.02027	0.02110	0.961	99.838	4.259	0.390	6.475	410.9	97.8
266.	55.5	81.0	21.0	3.61	205.5	10.0	0.01790	0.01810	0.989	99.816	4.454	0.661	5.013	306.4	73.0
267.	43.0	117.0	16.0	3.36	165.9	9.0	0.01666	0.01580	1.054	99.773	6.904	0.541	4.168	225.7	53.7
268.	61.5	140.0	14.5	3.55	171.4	17.0	0.01762	0.01640	1.075	99.752	7.816	0.464	5.640	227.8	54.2
269.	46.0	121.0	20.5	3.08	143.0	11.0	0.01526	0.01550	0.984	99.731	7.785	0.755	4.861	164.7	39.2
270.	37.0	127.0	[illegible]8.5	2.96	113.9	5.0	0.01466	0.01450	1.011	99.722	8.499	0.709	4.067	102.9	24.5
271.	21.3	252.0	46.5	2.52	78.6	2.0	0.01254	0.01180	1.063	99.349	19.673	2.079	2.731	29.9	7.1
272.	17.0	407.0	85.0	2.33	67.8	3.0	0.01169	0.01110	1.053	98.842	34.053	4.072	2.336	5.0	1.2
273.	17.2	407.0	87.0	2.33	67.8	1.0	0.01169	0.01110	1.053	98.833	34.050	4.168	2.364	5.0	1.2
274.	18.2	248.0	50.0	2.40	78.6	2.0	0.01194	0.01180	1.012	99.311	20.318	2.346	2.449	30.6	7.3
275.	36.5	140.0	41.0	3.10	116.0	7.0	0.01538	0.01460	1.053	99.644	8.938	1.499	3.827	107.5	25.6
276.	43.0	134.0	34.0	2.95	145.0	12.0	0.01462	0.01560	0.937	99.655	8.991	1.306	4.739	169.1	40.3
277.	56.0	158.0	32.0	3.50	171.9	20.0	0.01739	0.01650	1.054	99.678	8.938	1.037	5.203	229.4	54.6
278.	41.0	128.0	34.5	3.33	168.4	8.0	0.01652	0.01620	1.020	99.702	7.615	1.175	4.006	229.5	54.6
279.	52.0	100.0	32.0	3.61	204.6	9.0	0.01791	0.01810	0.990	99.763	5.494	1.007	4.693	310.7	74.0
280.	53.0	101.0	26.5	3.59	205.5	9.0	0.01781	0.01810	0.984	99.775	5.581	0.838	4.810	306.1	73.3
281.	42.0	134.0	37.0	3.42	166.9	6.0	0.01698	0.01600	1.061	99.694	7.761	1.227	3.995	224.5	53.5
282.	58.5	156.0	35.0	3.59	170.9	20.0	0.01784	0.01640	1.088	99.679	8.604	1.105	5.300	225.4	53.7
283.	43.0	136.0	31.0	3.01	143.5	11.0	0.01492	0.01580	0.944	99.669	8.945	1.168	4.645	164.1	39.1
284.	36.5	147.0	39.0	3.00	114.5	7.0	0.01488	0.01460	1.019	99.628	9.694	1.473	3.954	102.8	24.5
285.	25.0	324.0	66.0	2.26	74.7	2.0	0.01129	0.01170	0.965	99.046	28.054	3.272	3.555	23.6	5.6
286.	25.0	398.0	97.0	2.15	67.5	4.0	0.01080	0.01100	0.982	98.706	36.021	5.027	3.716	4.2	1.0

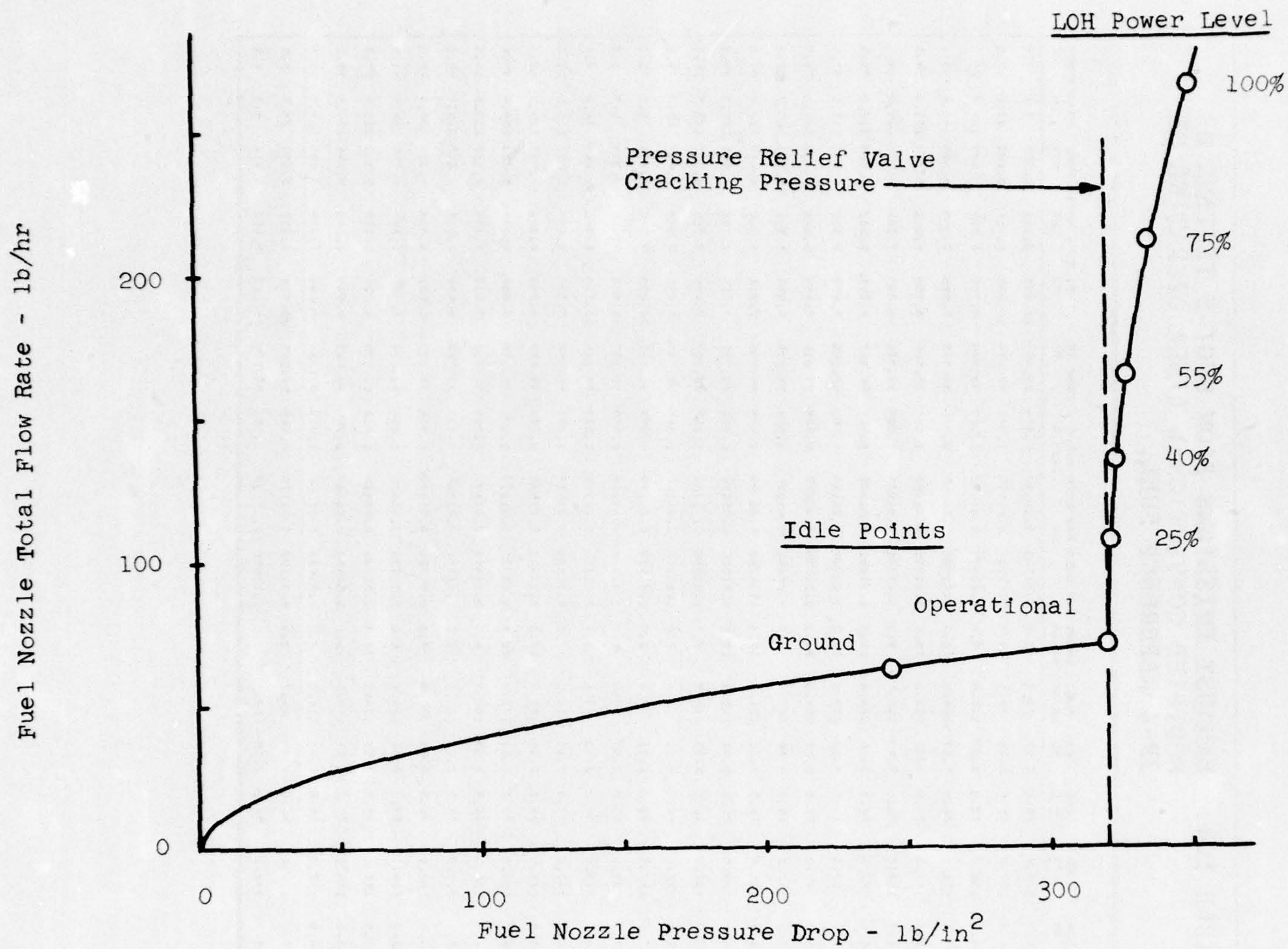

Figure 208. Estimated Performance of Airblast Fuel Nozzle EX-115870C for use with Modified Conventional Combustor.

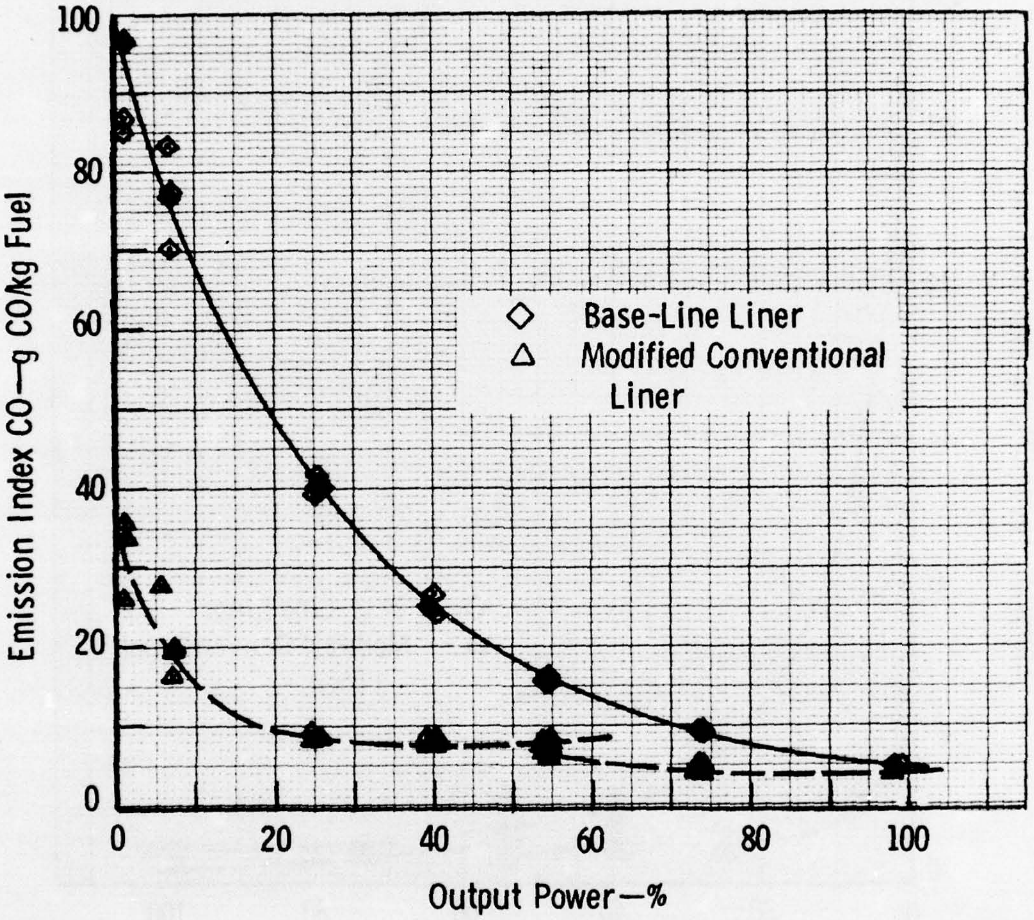

Figure 209. Modified Conventional and Baseline Engine Exhaust Carbon Monoxide Emissions.

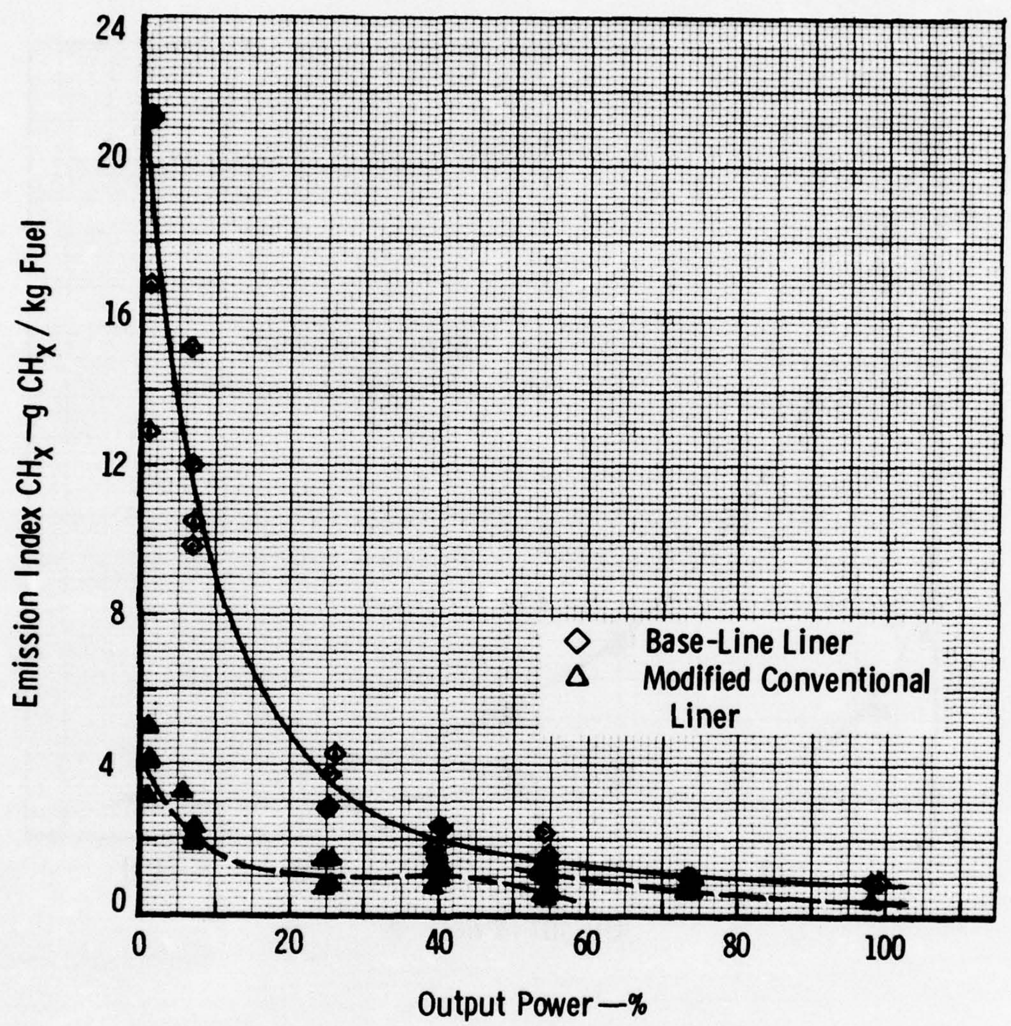

Figure 210. Modified Conventional and Baseline Engine Exhaust Unburned Hydrocarbons.

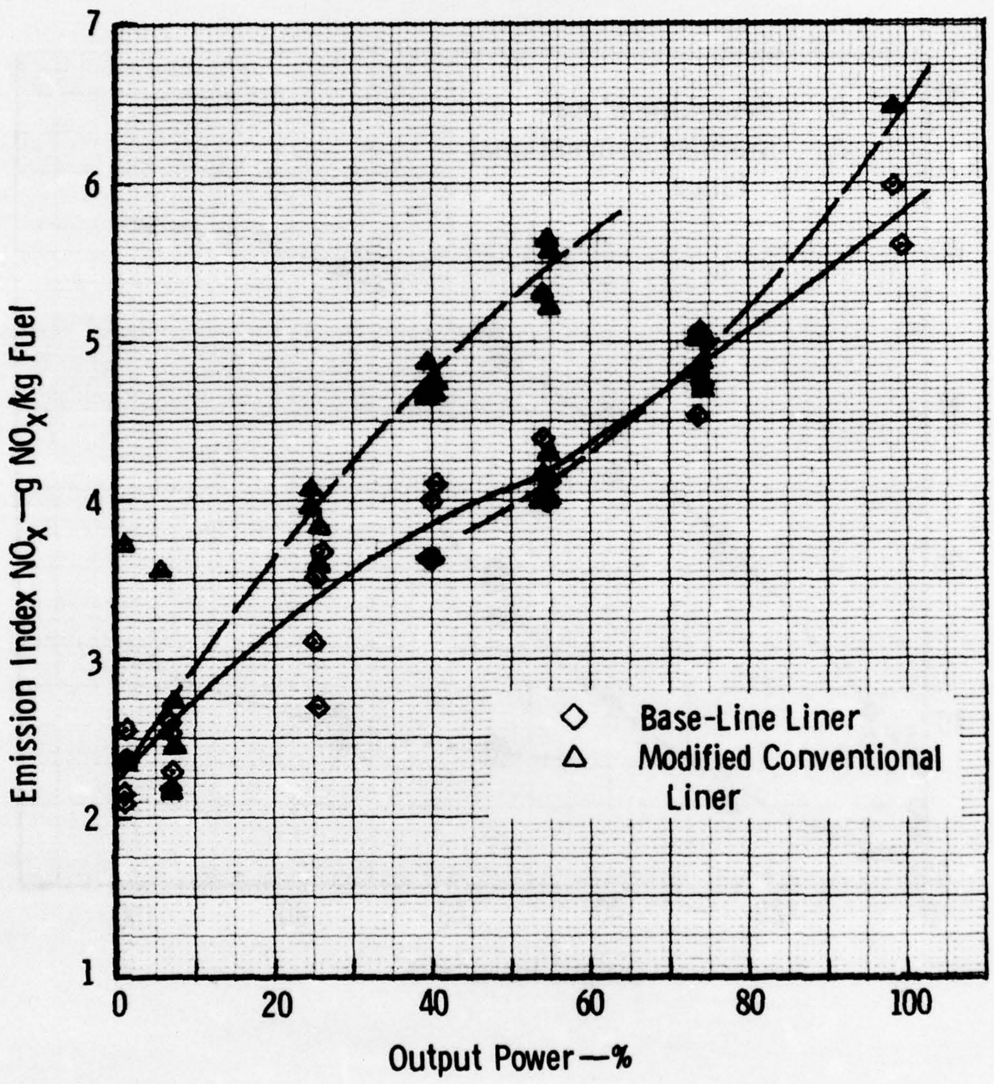

Figure 211. Modified Conventional and Baseline Engine Exhaust Total Nitrogen Oxide Emissions.

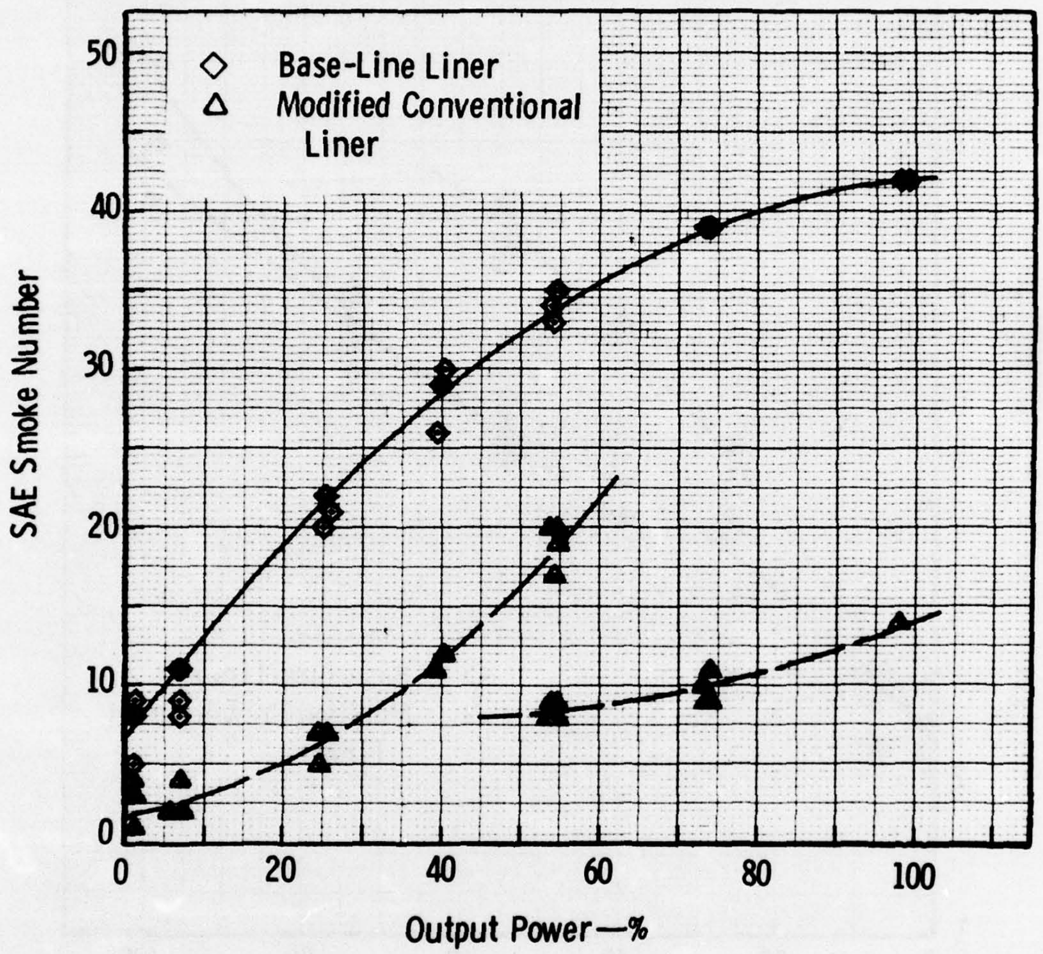

Figure 212. Modified Conventional and Baseline Engine Exhaust Smoke.

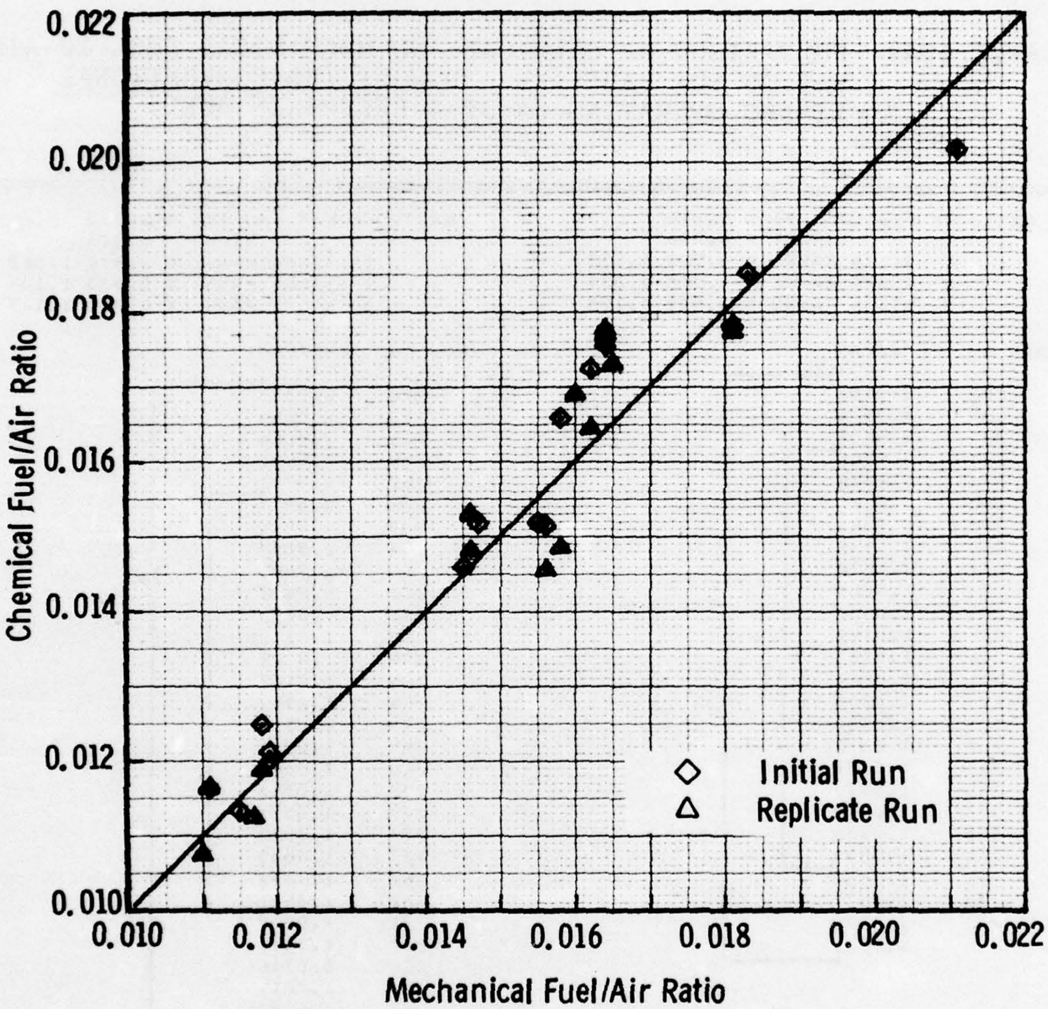

Figure 213. Modified Conventional Liner Mechanical and Chemical Fuel-to-Air Ratio Comparison from Engine Test.

TABLE 105. COMPARISON OF CHEMICAL AND MECHANICAL FUEL-TO-AIR RATIOS FOR BASELINE AND MODIFIED CONVENTIONAL LINERS OPERATING ON JP-4 REFERENCE FUEL.

Baseline Liner 6871486

RATIO OF F/A C/M AVG = 1.016
SIGMA = 0.036
1 SIGMA RANGE = 0.981 1.052
2 SIGMA RANGE = 0.945 1.088
3 SIGMA RANGE = 0.909 1.124

RDG NO	FAC/FAM
242	0.9452
254	0.9576
234	0.9606
247	0.9746
241	0.9834
255	0.9835
248	0.9849
235	0.9971
237	1.0028
239	1.0029
243	1.0050
238	1.0121
244	1.0202
231	1.0244
240	1.0246
245	1.0303
252	1.0370
249	1.0377
250	1.0395
253	1.0475
233	1.0483
246	1.0508
236	1.0569
232	1.0577
257	1.0720
256	1.0721

σ 2σ

Modified Conventional Liner EX-119066

RATIO OF F/A C/M AVG = 1.019
SIGMA = 0.043
1 SIGMA RANGE = 0.976 1.062
2 SIGMA RANGE = 0.933 1.104
3 SIGMA RANGE = 0.890 1.147

RDG NO	FAC/FAM
276	0.9373
283	0.9444
265	0.9606
285	0.9652
261	0.9751
286	0.9817
280	0.9840
269	0.9844
266	0.9889
279	0.9897
256	0.9899
270	1.0110
274	1.0121
264	1.0167
284	1.0192
278	1.0199
259	1.0225
260	1.0369
272	1.0533
275	1.0533
273	1.0534
277	1.0539
267	1.0543
281	1.0611
271	1.0628
263	1.0686
265	1.0746
262	1.0811
282	1.0880

σ 2σ

TABLE 106. BASELINE AND MODIFIED CONVENTIONAL MECHANICAL FUEL-TO-AIR RATIOS FROM MODEL 250-C20B EMISSION TEST

	Shaft Hp	First Run UP	First Run Down	Second Run UP	Second Run Down
Baseline Liner	5	.0113	.0112	.0113	.0112
Rdgs 232-257	25	.0118	.0118	.0117	.0117
	105	.0145	.0145	.0144	.0145
	168	.0151	.0152	.0151	.0153
	231	.0158	.0158	.0160	.0160
	315	.0180	.0180	.0181	.0179
	420	.0209	-	.0209	-
Modified Conventional					
Liner	5L	.0115	.0111	.0111	.0110
EX-119066	25L	.0119	.0118	.0118	.0117
Rdgs 258-286	105L	.0147	.0145	.0146	.0146
	168L	.0156	.0155	.0156	.0158
	231L	.0164	.0164	.0165	.0164
	231H	.0162	.0158	.0162	.0160
	315H	.0183	.0181	.0181	.0181
	420H	.0211	-	-	-

TABLE 107. AVERAGE EXHAUST EMISSIONS AT LOH DUTY CYCLE POINTS FROM ENGINE TESTING OF MODIFIED CONVENTIONAL LINER

MODIFIED CONVENTIONAL LINER, EX-119066, JP-4 REF, APRIL ENGINE TEST SERIES DATA

RDG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
1.	17.0	375.0	80.0	2.28	69.0	2.2	0.01142	0.00000	0.000	98.900	32.100	3.921	2.390	5.0	1.2
6.	20.2	270.0	51.0	2.43	77.0	2.6	0.01210	0.00000	0.000	99.274	21.830	2.361	2.683	25.0	6.0
25.	34.0	140.0	31.0	3.05	114.5	6.6	0.01512	0.00000	0.000	99.672	9.086	1.152	3.624	105.0	25.0
40.	46.6	120.0	22.0	3.07	144.5	11.8	0.01521	0.00000	0.000	99.727	7.745	0.813	4.940	168.0	40.0
551.	60.0	120.0	17.0	3.60	171.0	18.8	0.01767	0.00000	0.000	99.775	6.610	0.536	5.429	231.0	55.0
552.	42.8	140.0	35.0	3.41	171.0	8.6	0.01693	0.00000	0.000	99.691	8.131	1.164	4.083	231.0	55.0
75.	55.8	95.0	23.0	3.67	210.0	10.3	0.01621	0.00000	0.000	99.796	5.136	0.712	4.955	315.0	75.0
100.	84.0	85.0	13.0	4.17	264.0	14.7	0.02075	0.00000	0.000	99.845	4.043	0.354	6.563	420.0	100.0

averaged over the LOH duty cycle and are compared to the baseline emissions in Table 108. The difference between the two modified conventional portions of the table is the dilution geometry setting used at 55% power conditions. One set used the low power setting and produced the lower overall emissions but 15% more NO_x than the baseline liner produced. The other set used the high power dilution setting at 55% power and suppressed the NO_x, but the total emissions increased slightly. The high dilution setting results showed that over the LOH duty cycle the modified conventional combustor system reduced CH_x by more than 51%, CO by nearly 60%, while NO_x was maintained at nearly baseline level (actually a 1.4% increase), and total emissions were reduced 48.3% (only 1.7% from the 50% goal).

RIG-TO-ENGINE DATA CORRELATION

Two combustor rig tests and three engine tests were conducted using the production baseline combustor system of the Model 250-C20B engine. Of the two rig tests, the initial rig test, in which emissions, combustor performance, and liner skin temperatures were documented, was found to be in error due to mechanical deficiencies in the rig instrumentation ring at the liner exit. Therefore, after rebuilding the instrumentation section, the emissions and combustor performance tests were repeated, but the thermal paint test to document liner metal temperatures at 100% power was not repeated.

Engine calibration with the production baseline liner was performed to document exhaust emissions, the liner exit temperature profile, and the engine performance. An air regulator failure ruined the first set of the exhaust emissions data by ingesting ambient air into the sample line. The exhaust emissions baseline was repeated prior to the engine testing of the low-emission combustors. The final engine recalibration, including exhaust emissions, followed the prechamber combustor multiple-fuels testing.

Fuel flows and fuel-air ratios from the three valid exhaust-emissions tests (one rig and two engine) are plotted against percent output horsepower in Figures 214 and 215. The fuel flow rates are all very close, but the fuel-air ratios from the combustor rig were higher at the higher power levels. The test data from each of these runs are given in Tables 109, 110, and 111 for the baseline final calibration, baseline initial calibration, and valid rig baseline, respectively.

TABLE 108. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS FROM ENGINE TEST OF MODIFIED CONVENTIONAL LINER.

BASELINE LINER, 6871486, JP-4 REFERENCE FUEL, APRIL ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	70.00	17.354	92.163	2.250	111.767	6.80
6.	0.15	78.00	12.110	78.205	2.359	92.674	9.80
25.	0.00	116.00	3.535	41.387	2.996	47.918	20.50
40.	0.15	143.00	1.959	24.852	3.605	30.416	28.40
55.	0.45	170.00	1.411	17.058	4.514	22.983	34.50
75.	0.20	209.00	1.008	9.337	4.952	15.297	39.20
100.	0.05	262.00	1.080	5.522	5.782	12.384	42.10
CYCLE TOTALS		164.55	2.114	19.542	4.454	26.111	42.10
PERCENT OF BASELINE		100.00	100.00	100.00	100.00	100.00	

MODIFIED CONVENTIONAL LINER, EX-119066, JP-4 REF, 55% LOW DZ, APRIL ENGINE TEST

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	69.00	3.921	32.100	2.390	38.411	2.20
6.	0.15	77.00	2.361	21.830	2.683	26.874	2.60
25.	0.00	114.50	1.152	9.086	3.624	13.862	6.60
40.	0.15	144.50	0.813	7.745	4.940	13.498	11.80
551.	0.45	171.00	0.536	6.610	5.429	12.575	18.80
75.	0.20	210.00	0.712	5.136	4.955	10.803	10.30
100.	0.05	264.00	0.354	4.043	6.563	10.960	14.70
CYCLE TOTALS		165.37	0.730	7.242	5.143	13.116	18.80
PERCENT OF BASELINE		100.50	34.52	37.06	115.46	50.23	

MODIFIED CONVENTIONAL LINER, EX-119066, JP-4 REF, 55% HIGH DZ, APRIL ENGINE TEST

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	69.00	3.921	32.100	2.390	38.411	2.20
6.	0.15	77.00	2.361	21.830	2.683	26.874	2.60
25.	0.00	114.50	1.152	9.086	3.624	13.862	6.60
40.	0.15	144.50	0.813	7.745	4.940	13.498	11.80
552.	0.45	171.00	1.164	8.131	4.083	13.378	8.60
75.	0.20	210.00	0.712	5.136	4.955	10.803	10.30
100.	0.05	264.00	0.354	4.043	6.563	10.960	14.70
CYCLE TOTALS		165.37	1.022	7.950	4.517	13.489	14.70
PERCENT OF BASELINE		100.50	48.34	40.68	101.40	51.66	

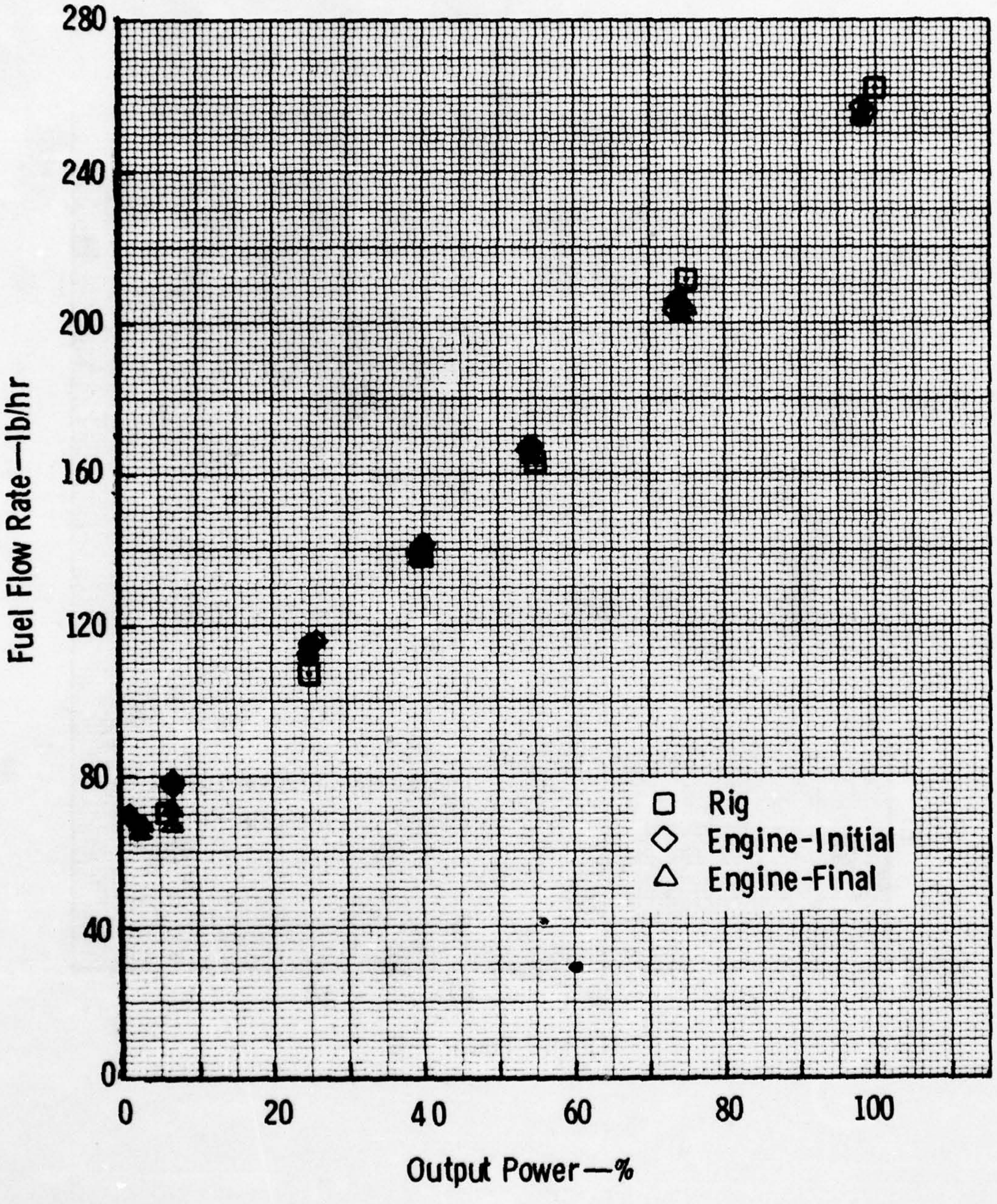

Figure 214. Baseline Liner Rig and Engine Fuel Flow Rates at Percent Output Power.

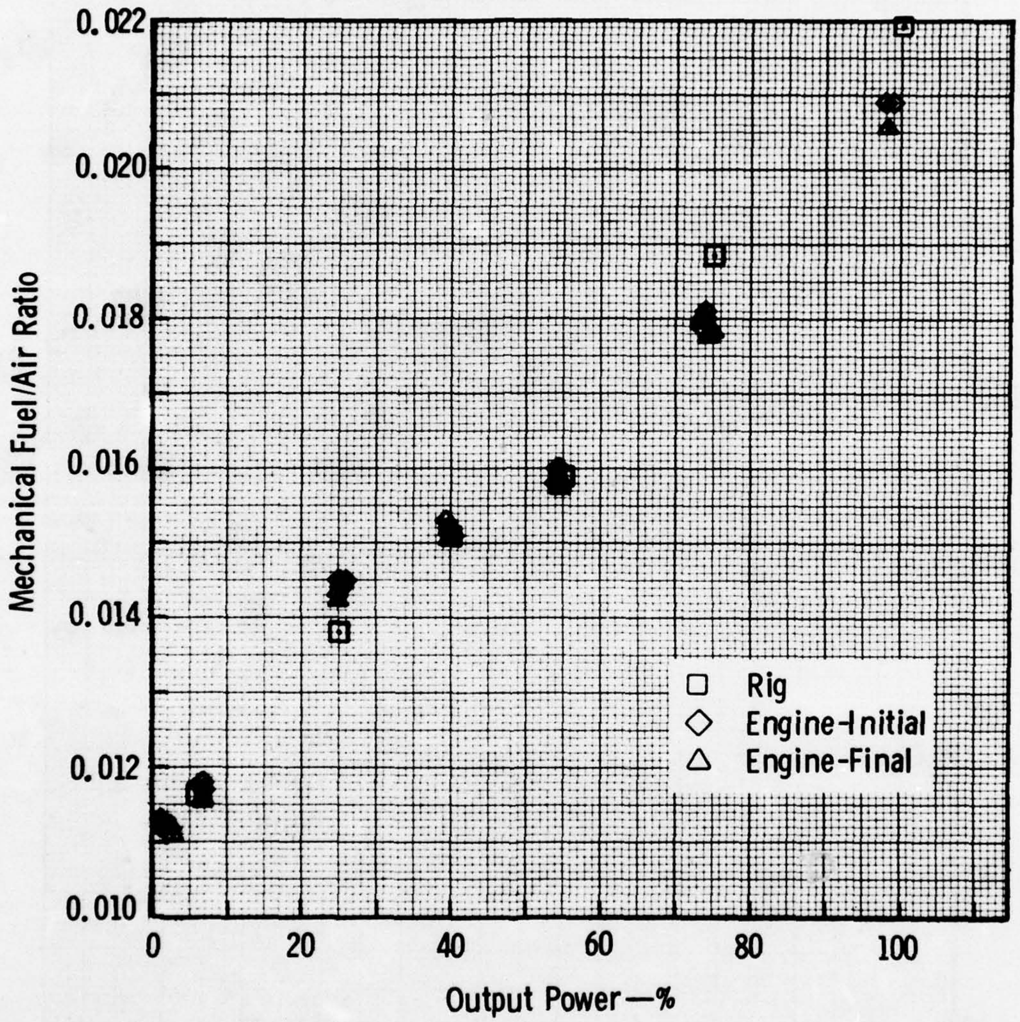

Figure 215. Baseline Liner Rig and Engine Mechanical Fuel-to-Air Ratios at Output Power.

TABLE 109. EXHAUST EMISSIONS FROM ENGINE TESTING OF BASELINE MODEL 250-C20B COMBUSTOR, FINAL TEST

RDG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
354.	17.2	1680.0	390.0	2.28	65.2	11.0	0.01213	0.01123	1.080	95.242	135.501	18.012	2.279	10.2	2.4
355.	17.5	1810.0	420.0	2.40	67.1	14.0	0.01281	0.01159	1.105	95.141	138.417	18.392	2.198	28.6	6.8
356.	28.0	700.0	110.0	2.83	113.7	27.0	0.01423	0.01435	0.992	98.476	48.235	4.340	3.169	104.5	24.9
357.	36.0	470.0	60.5	3.10	139.4	34.0	0.01543	0.01519	1.016	99.089	29.900	2.204	3.762	166.8	39.7
358.	43.0	317.0	46.5	3.35	164.4	39.0	0.01659	0.01573	1.055	99.403	18.777	1.577	4.184	229.2	54.6
359.	57.0	206.0	36.0	3.70	203.8	43.0	0.01828	0.01782	1.026	99.620	11.095	1.110	5.043	314.9	75.0
360.	78.5	125.0	31.5	4.38	254.2	46.0	0.02165	0.02056	1.053	99.768	5.704	0.823	5.884	412.4	98.2
361.	55.5	210.0	32.0	3.69	201.8	43.0	0.01823	0.01775	1.027	99.625	11.341	0.990	4.923	312.2	74.3
362.	44.0	335.0	37.0	3.34	164.7	38.0	0.01655	0.01586	1.043	99.404	19.897	1.258	4.292	228.8	54.5
363.	37.0	465.0	47.0	3.08	137.8	33.0	0.01532	0.01505	1.018	99.133	29.789	1.724	3.893	166.5	39.6
364.	28.5	680.0	80.0	2.83	112.4	27.0	0.01421	0.01423	0.998	98.608	46.938	3.162	3.231	104.7	24.9
365.	19.4	1490.0	295.0	2.40	71.3	14.0	0.01259	0.01154	1.091	96.124	115.912	13.141	2.479	28.3	6.7
366.	18.2	1490.0	305.0	2.30	67.3	12.0	0.01210	0.01110	1.090	95.930	120.540	14.129	2.418	11.8	2.8

TABLE 110. EXHAUST EMISSIONS FROM ENGINE TEST OF BASELINE MODEL 250-C20B COMBUSTOR, INITIAL TEST (PART 1 OF 2)

RDG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
232.	16.0	1040.0	275.0	2.30	69.9	5.0	0.01195	0.01130	1.058	96.882	85.143	12.892	2.152	4.2	1.0
233.	19.5	890.0	265.0	2.40	79.1	9.0	0.01237	0.01180	1.048	97.300	70.430	12.008	2.535	28.8	6.8
234.	31.8	575.0	107.0	2.76	116.0	21.0	0.01393	0.01450	0.961	98.665	40.471	4.313	3.676	109.1	26.0
235.	38.3	375.0	63.0	3.01	141.5	30.0	0.01506	0.01510	0.997	99.208	24.445	2.352	4.101	169.3	40.3
236.	42.6	268.0	48.0	3.35	167.4	35.0	0.01670	0.01580	1.057	99.473	15.776	1.618	4.119	229.3	54.6
237.	56.0	173.0	30.0	3.63	205.5	39.0	0.01805	0.01800	1.003	99.676	9.434	0.937	5.016	310.6	73.9
238.	78.0	113.0	33.5	4.25	256.9	42.0	0.02115	0.02090	1.012	99.772	5.275	0.895	5.980	411.5	98.0
239.	56.5	174.0	33.0	3.63	205.5	39.0	0.01805	0.01800	1.003	99.666	9.488	1.030	5.060	308.8	73.5
240.	44.0	263.0	35.5	3.25	166.4	34.0	0.01619	0.01580	1.025	99.501	15.962	1.234	4.386	226.1	53.8
241.	37.0	381.0	41.0	2.99	141.0	29.0	0.01495	0.01520	0.983	99.266	25.013	1.541	3.990	166.9	39.7
242.	29.9	565.0	71.0	2.72	115.0	22.0	0.01371	0.01450	0.945	98.791	40.405	2.907	3.512	105.8	25.2
243.	19.2	1010.0	320.0	2.28	78.6	11.0	0.01186	0.01180	1.005	96.728	83.321	15.117	2.602	27.8	6.6
244.	16.8	1125.0	433.0	2.17	69.4	8.0	0.01143	0.01120	1.020	95.892	96.288	21.222	2.362	5.0	1.2
245.	18.5	1150.0	443.0	2.21	69.2	9.0	0.01164	0.01130	1.030	95.875	96.620	21.313	2.553	5.0	1.2

TABLE 110. EXHAUST EMISSIONS FROM ENGINE TEST OF BASELINE MODEL 250-C20B COMBUSTOR, INITIAL TEST (PART 2 OF 2)

RDG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
246.	17.5	975.0	230.0	2.38	78.0	11.0	0.01229	0.01170	1.051	97.268	77.619	10.485	2.288	29.4	7.0
247.	23.5	600.0	94.0	2.78	115.0	22.0	0.01403	0.01440	0.975	98.685	41.917	3.760	2.697	106.6	25.4
248.	33.5	408.0	63.0	2.97	141.0	29.0	0.01487	0.01510	0.985	99.150	26.919	2.380	3.630	168.1	40.0
249.	41.0	282.0	42.0	3.33	166.9	35.0	0.01660	0.01600	1.038	99.469	16.695	1.424	3.987	228.4	54.4
250.	55.0	187.0	33.0	3.78	206.0	39.0	0.01881	0.01810	1.039	99.665	9.791	0.989	4.730	310.4	73.9
251.	74.0	117.0	36.0	4.30	255.5	42.0	0.02141	0.02090	1.024	99.766	5.397	0.951	5.607	415.7	99.0
252.	52.0	185.0	34.0	3.73	203.2	39.0	0.01856	0.01790	1.037	99.661	9.815	1.033	4.532	307.6	73.2
253.	41.5	270.0	66.0	3.36	167.4	33.0	0.01676	0.01600	1.047	99.420	15.838	2.217	3.998	227.0	54.1
254.	33.0	380.0	47.0	2.93	139.0	26.0	0.01465	0.01530	0.958	99.235	25.446	1.802	3.630	165.1	39.3
255.	27.5	575.0	72.0	2.83	115.0	20.0	0.01426	0.01450	0.984	98.819	39.542	2.835	3.106	104.9	25.0
256.	17.0	985.0	220.0	2.43	77.3	8.0	0.01254	0.01170	1.072	97.343	76.878	9.833	2.179	28.8	6.9
257.	15.6	1065.0	360.0	2.30	69.4	8.0	0.01201	0.01120	1.072	96.501	86.797	16.801	2.088	4.7	1.1

TABLE 111. EXHAUST EMISSIONS FROM RIG TEST OF BASELINE MODEL 250-C20B COMBUSTOR

TESTED 6-18-74

RDG NO	NOX PPM	CO PPM	CHX PPM C	CO2 PC	FUEL LB/HR	SMOKE NUMBER	F/A CHEM	F/A MECH	F/A C / F/A M	COMB EF PC	E. I. - GM/KG FUEL CO	CHX	NOX	HORSEPOWER HP	PC
1333.	22.3	1081.4	522.9	2.45	70.4	11.1	0.01279	0.01164	1.099	96.069	82.801	22.927	2.805	25.0	6.0
1334.	32.6	786.1	228.9	3.03	107.3	20.8	0.01537	0.01381	1.113	98.091	50.210	8.372	3.420	105.0	25.0
1335.	38.5	587.4	77.4	3.31	138.2	27.0	0.01661	0.01510	1.100	98.950	34.754	2.622	3.741	168.0	40.0
1338.	53.7	382.9	24.9	3.42	163.1	39.9	0.01700	0.01590	1.069	99.393	22.142	0.825	5.100	231.0	55.0
1339.	69.9	148.3	6.0	4.00	211.4	42.3	0.01981	0.01885	1.051	99.788	7.383	0.171	5.716	315.0	75.0
1340.	95.5	32.3	6.3	4.72	262.0	39.9	0.02337	0.02196	1.064	99.925	1.367	0.153	6.641	420.0	100.0

RATIO OF F/A C/M AVG = 1.083
SIGMA = 0.025
1 SIGMA RANGE = 1.058 1.107
2 SIGMA RANGE = 1.034 1.132
3 SIGMA RANGE = 1.009 1.156

RDG NO	FAC/FAM
1339	1.0507
1340	1.0642
1338	1.0694
1333	1.0987
1335	1.1001
1334	1.1129

Exhaust liner temperature profiles are given in Figures 216 and 217 for 75% power rig test and 82% power engine test, and in Figures 218 and 219 for 100% power rig and engine tests. These profiles have similar characteristics but are out of phase by 180°. From data taken on previous corporate programs, this flip-flop characteristic is well documented, but it makes final trimming for temperature profile a matter for engine testing and not rig testing. Figure 220 shows a comparison of rig and engine pattern factors as a function of output power. The agreement is good at high power.

The liner metal temperature comparisons using thermally sensitive paint were done on the rig when the instrumentation section was defective, thus influencing the liner performance. The exhaust temperatures from this test are shown in Figure 221. The temperature patterns from the same liner at the same operating condition are shown before repair (Figure 221) and after repair (Figure 218) of the rig instrumentation section. The combustor rig thermal paint test is shown in Figure 222 and the engine test in Figure 223. The patterns are fundamentally the same, but the very poor temperature profile in the rig test exaggerated the temperature gradient aft of the dilution holes. Here again, what is seen on the rig is not necessarily what will be experienced on the engine. Another comparison of rig-engine metal temperatures is given in Figure 224. These temperatures are from five thermocouples attached to the liner metal surface. These data agree very closely.

Using the data from Tables 109, 110, and 111 engine and rig baseline exhaust emissions were compared. Chemical fuel-air ratios and carbon dioxide data are presented in Figures 225 and 226. In general, the combustor rig values were higher, especially at the higher power levels. Combustion efficiencies are plotted in Figure 227. The rig data had lower efficiency at low power, but higher efficiency at the high-power levels. The plots of unburned hydrocarbon and carbon monoxide emissions versus power in Figures 228 and 229, also show a crossover between engine and rig data at mid power. Engine hydrocarbons reach a minimum or floor level primarily because of oil leakage through seals. Nitrogen oxides emissions (Figure 230) were consistently higher than in the combustor rig testing, but the smoke data in Figure 231 appeared to be the same in both rig and engine tests. Each of the sets of rig and engine exhaust emissions data were time-weight averaged over the LOH duty cycle as given in Table 112. The percentage emissions were computed using the rig data as the reference, i.e., the combustor rig test percentages are all 100%. The initial baseline emissions test produced lower emissions index values for all constituents. In the final baseline test, however, emissions were back up to and slightly higher than baseline CO and CH_x values while the NO_x levels remained the same as the initial baseline.

PRODUCTION BASELINE COMBUSTOR RIG TEST (REPEAT) AT 75% POWER CONDITIONS
TEST DATE = 6-18-74 READING NUMBER = 1339 INLET TEMP = 515.
ENGINE NUMBER/NAME = COMB. RIG / MODEL 250-C20B ENGINE TOT = 1255.
OUTER CASE NUMBER/NAME = 6870992 / PRODUCTION BASELINE
LINER NUMBER/NAME = 6871486 / PRODUCTION BASELINE

	* * * * * A N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1784.1	1790.3	1679.6	1751.3
MAXIMUM TEMPERATURE	1909.0	1929.0	1899.0	1929.0
(AVG-INLET) TEMP	1269.1	1275.3	1164.6	1236.3
(MAX-AVG) TEMP	124.9	138.7	219.4	177.7
MAX TEMP/AVG TEMP	1.0700	1.0775	1.1306	1.1014
(MAX-AVG)/(AVG-IN)	0.0984	0.1088	0.1884	0.1437
(AVG-AVG TOTAL)	32.8	39.0	-71.8	
(TIP-HUB) AVG TEMP				-104.6
(AVG TOTAL-TOT)				496.3

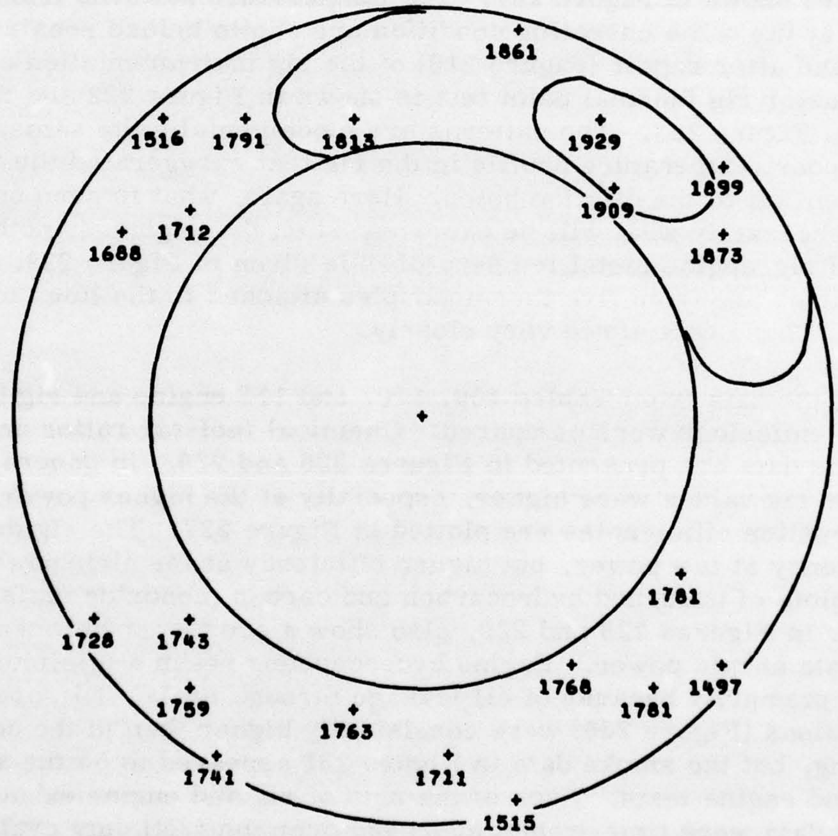

Figure 216. Baseline Liner Rig Measured Combustor Exit Temperatures at 75% Power.

BASELINE COMBUSTOR SYSTEM OPERATING AT 75% POWER TURBINE TEMPERATURE
TEST DATE = 10-11-74 READING NUMBER = 204 INLET TEMP = 529.
ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 1330.
OUTER CASE NUMBER/NAME = EX-115283 / INSTRUMENTED PROD.
LINER NUMBER/NAME = 6871486 / PRODUCTION BASELINE

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1749.3	1823.7	1865.6	1814.3
MAXIMUM TEMPERATURE	1880.0	1930.0	2010.0	2010.0
(AVG-INLET) TEMP	1220.3	1294.7	1336.6	1285.3
(MAX-AVG) TEMP	130.7	106.2	144.4	195.7
MAX TEMP/AVG TEMP	1.0747	1.0583	1.0774	1.1079
(MAX-AVG)/(AVG-IN)	0.1071	0.0821	0.1080	0.1523
(AVG-AVG TOTAL)	-64.9	9.5	51.4	
(TIP-HUB) AVG TEMP				116.3
(AVG TOTAL-TOT)				484.3

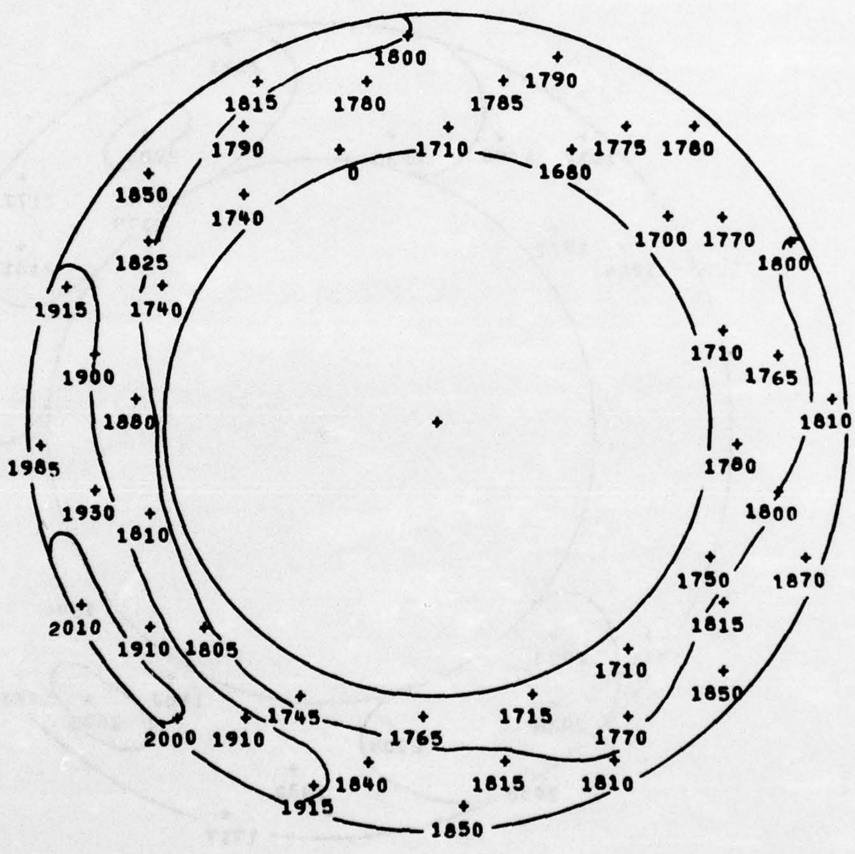

Figure 217. Baseline Liner Engine Measured Combustor Exit Temperatures at 75% Power.

PRODUCTION BASELINE COMBUSTOR RIG TEST (REPEAT) AT 100% POWER CONDITIONS
TEST DATE = 6-18-74 READING NUMBER = 1340 INLET TEMP = 569.
ENGINE NUMBER/NAME = COMB. RIG / MODEL 250-C20B ENGINE TOT = 1490.
OUTER CASE NUMBER/NAME = 6870992 / PRODUCTION BASELINE
LINER NUMBER/NAME = 6871486 / PRODUCTION BASELINE

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	2020.3	2035.9	1938.0	1998.0
MAXIMUM TEMPERATURE	2179.0	2209.0	2177.0	2209.0
(AVG-INLET) TEMP	1451.3	1466.9	1369.0	1429.0
(MAX-AVG) TEMP	158.7	173.1	239.0	211.0
MAX TEMP/AVG TEMP	1.0786	1.0850	1.1233	1.1056
(MAX-AVG)/(AVG-IN)	0.1094	0.1180	0.1746	0.1476
(AVG-AVG TOTAL)	22.2	37.8	-60.0	
(TIP-HUB) AVG TEMP				-82.3
(AVG TOTAL-TOT)				508.0

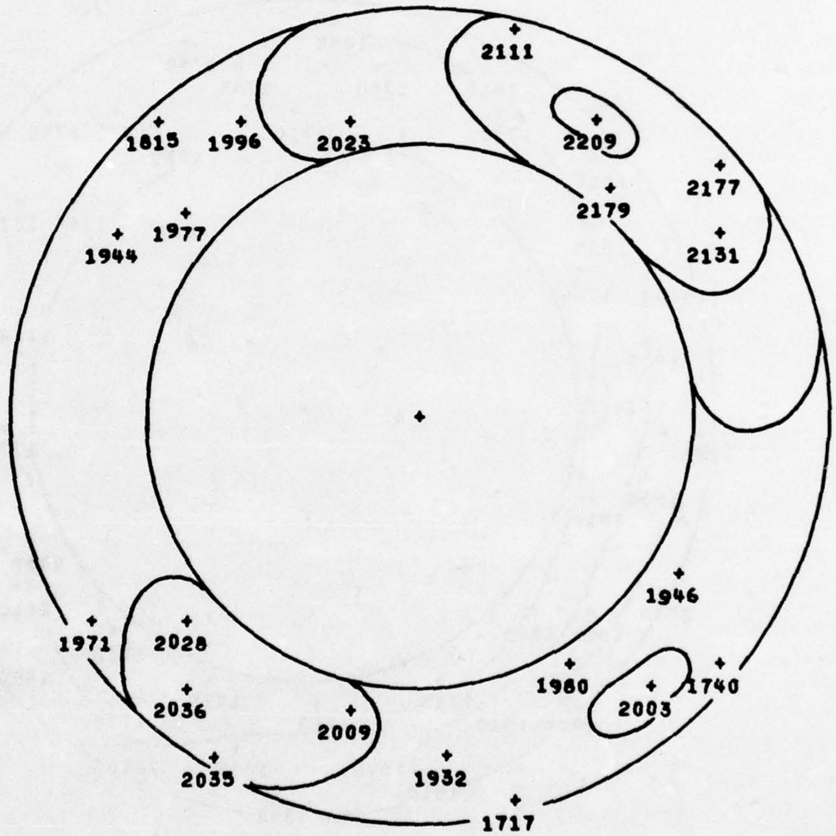

Figure 218. Baseline Liner Rig Measured Combustor Exit Temperatures at 100% Power.

BASELINE COMBUSTOR SYSTEM OPERATING AT 100% POWER TURBINE TEMPERATURE
TEST DATE = 10-11-74 READING NUMBER = 205 INLET TEMP = 564.
ENGINE NUMBER/NAME = CAE 821233 / MODEL 250-C20B ENGINE TOT = 1455.
OUTER CASE NUMBER/NAME = EX-115283 / INSTRUMENTED PROD.
LINER NUMBER/NAME = 6871466 / PRODUCTION BASELINE

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	1889.3	1976.2	2018.7	1963.0
MAXIMUM TEMPERATURE	2010.0	2085.0	2150.0	2150.0
(AVG-INLET) TEMP	1325.3	1412.2	1454.7	1399.0
(MAX-AVG) TEMP	120.7	108.7	131.2	187.0
MAX TEMP/AVG TEMP	1.0639	1.0550	1.0650	1.0953
(MAX-AVG)/(AVG-IN)	0.0910	0.0770	0.0902	0.1337
(AVG-AVG TOTAL)	-73.6	13.3	55.8	
(TIP-HUB) AVG TEMP				129.4
(AVG TOTAL-TOT)				508.0

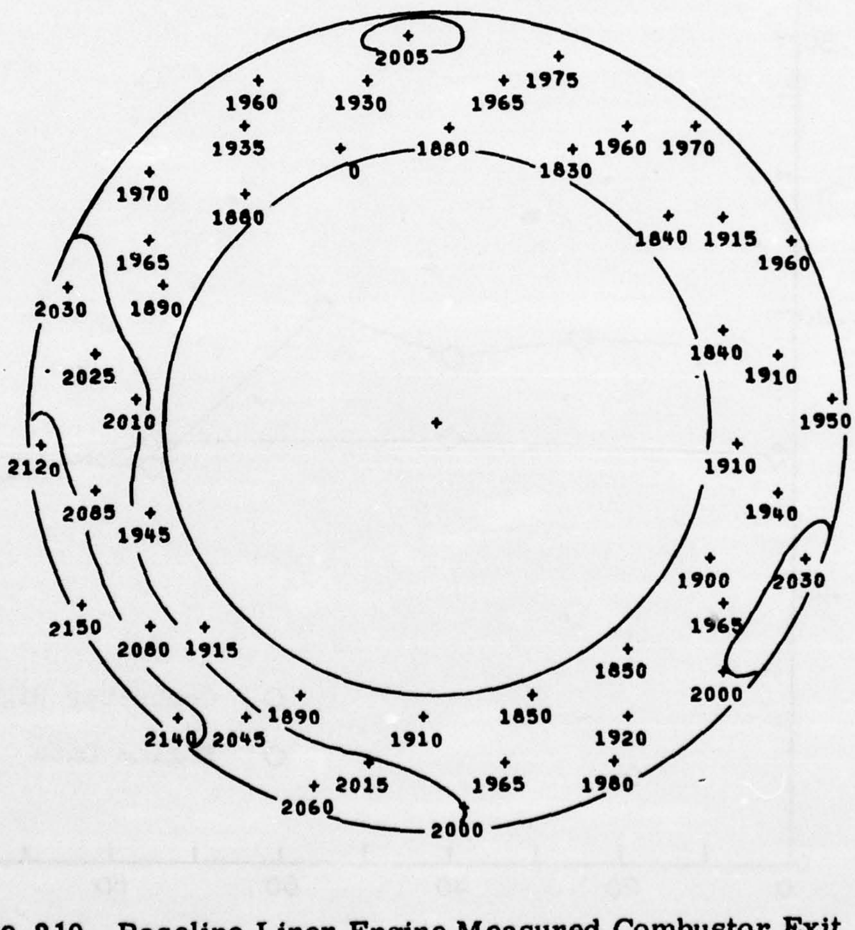

Figure 219. Baseline Liner Engine Measured Combustor Exit Temperatures at 100% Power.

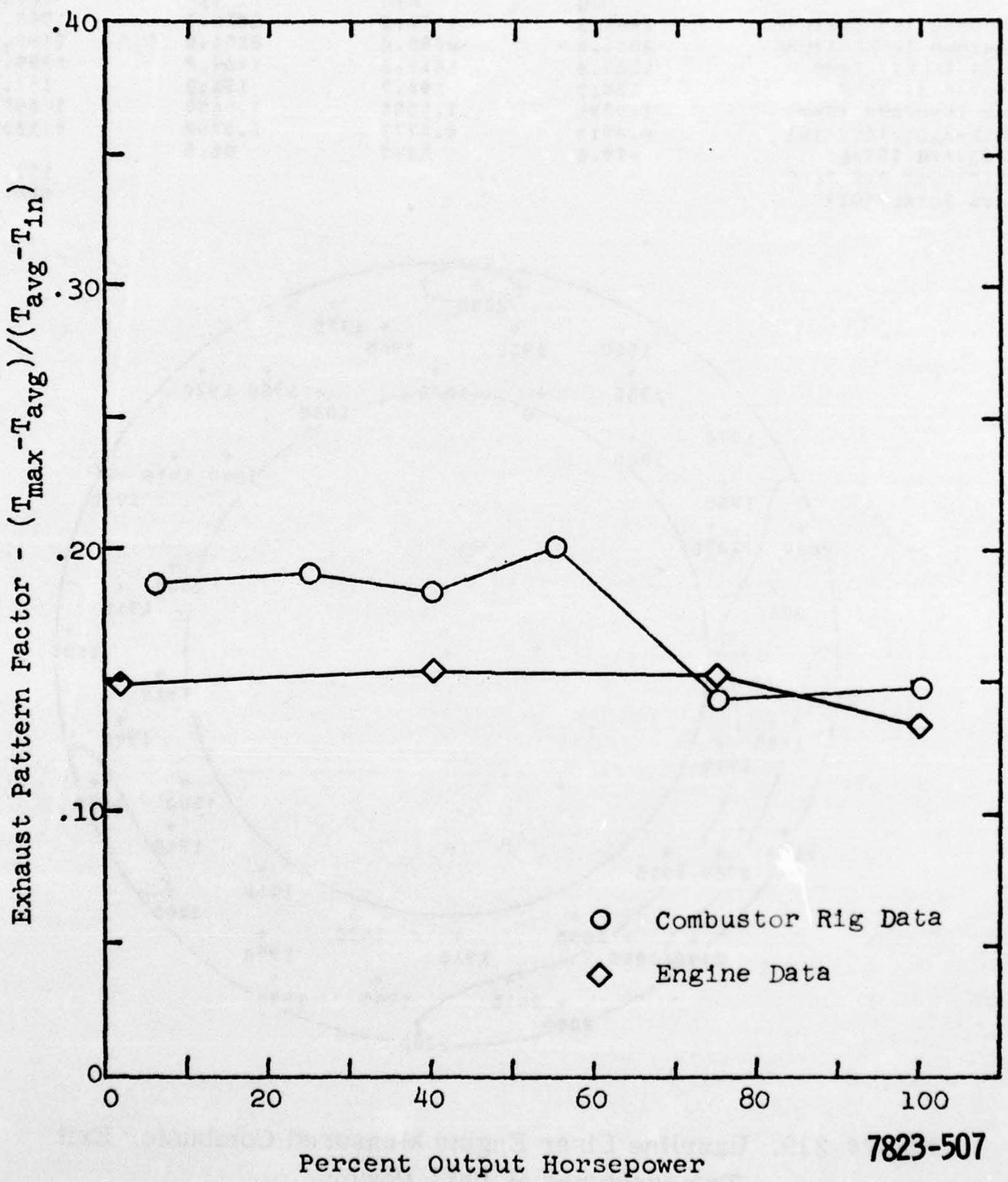

Figure 220. Baseline Liner Rig and Engine Pattern Factors at Percent Output Power.

PRODUCTION BASELINE COMBUSTOR RIG TEST AT 100% POWER DURING THERMAL PAINT RUN
TEST DATE = 4-27-74 READING NUMBER = 1305 INLET TEMP = 571.
ENGINE NUMBER/NAME = COMB. RIG / MODEL 250-C20B ENGINE TOT = 1490.
OUTER CASE NUMBER/NAME = 6870992 / PRODUCTION BASELINE
LINER NUMBER/NAME = 6871486 / PRODUCTION BASELINE

	* * * * * A N N U L U S * * * * *			
	HUB	MID	TIP	TOTAL
AVERAGE TEMPERATURE	2003.0	1962.7	1888.9	1951.5
MAXIMUM TEMPERATURE	2287.0	2250.0	2111.0	2287.0
(AVG-INLET) TEMP	1432.0	1391.7	1317.9	1380.5
(MAX-AVG) TEMP	284.0	287.3	222.1	335.5
MAX TEMP/AVG TEMP	1.1418	1.1464	1.1176	1.1719
(MAX-AVG)/(AVG-IN)	0.1983	0.2064	0.1686	0.2430
(AVG-AVG TOTAL)	51.5	11.2	-62.7	
(TIP-HUB) AVG TEMP				-114.1
(AVG TOTAL-TOT)				461.5

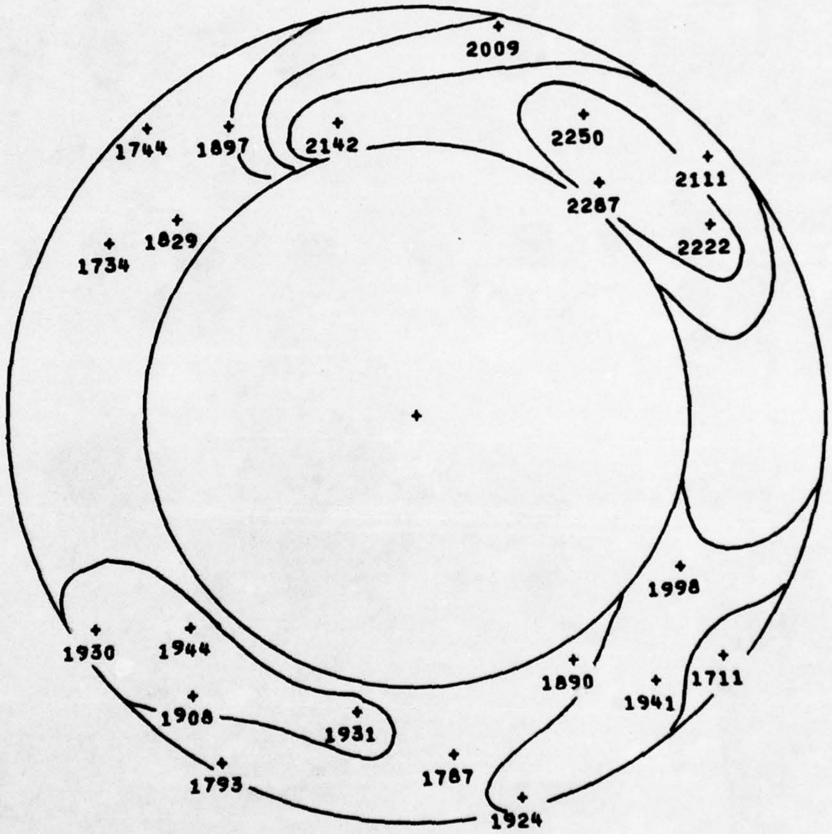

Figure 221. Baseline Liner Exhaust Temperature Measured During Rig Thermal Paint Run.

AD-A038 550 GENERAL MOTORS CORP INDIANAPOLIS IND DETROIT DIESEL --ETC F/G 21/5
LOW-EMISSIONS COMBUSTOR DEMONSTRATION. (U)
MAR 77 D L TROTH DAAJ02-74-C-0025
UNCLASSIFIED DDA-EDR-8723 USAAMRDL-TR-76-29 NL

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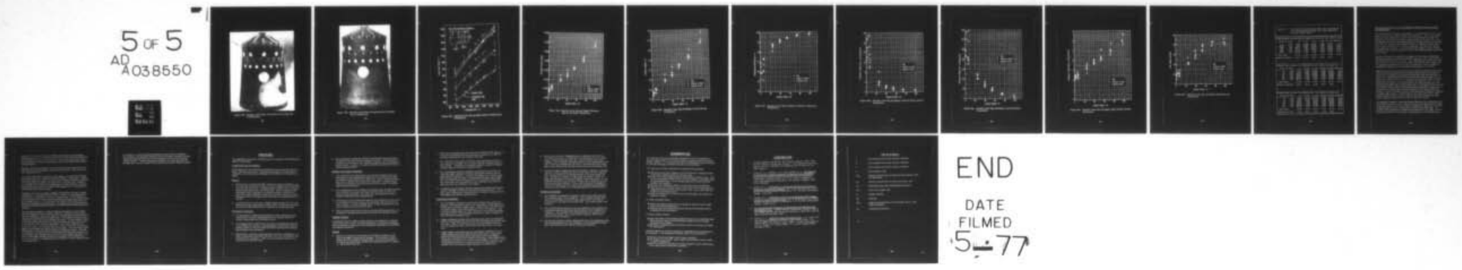
AD A038550



END
DATE
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5-77

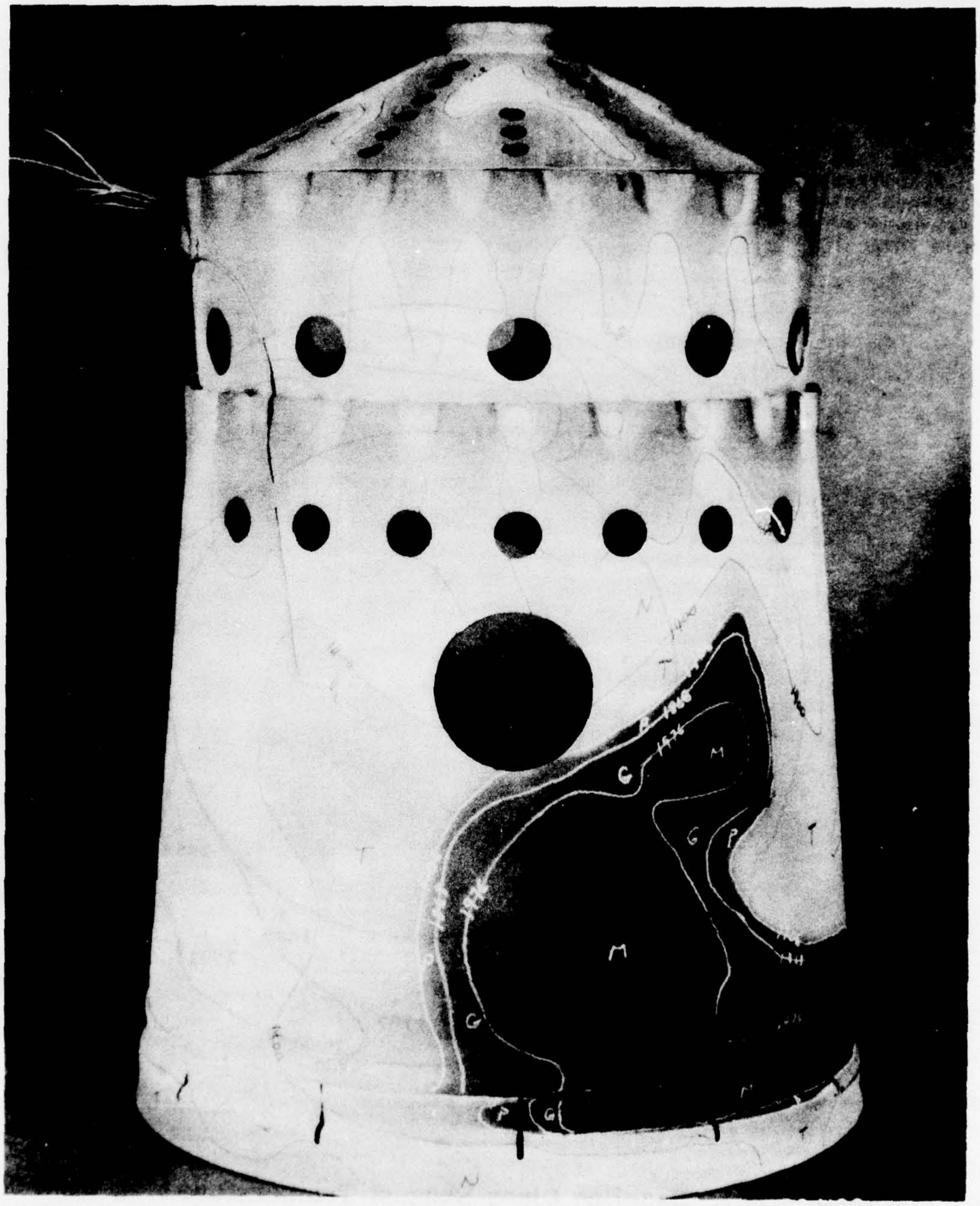

Figure 222. Baseline Liner Metal Temperatures from Rig Test at 100% Power.

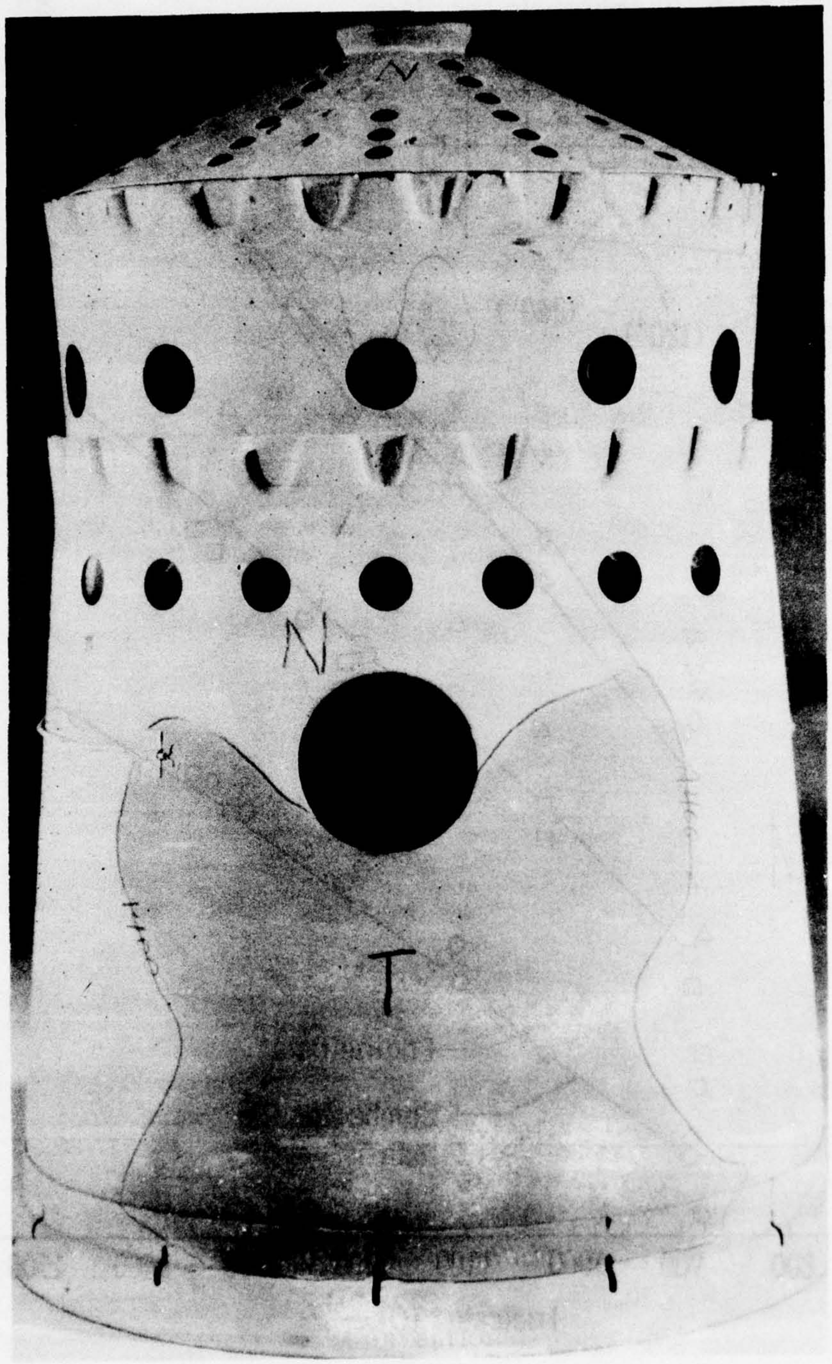

Figure 223. Baseline Liner Metal Temperatures from Engine Test at 100% Power.

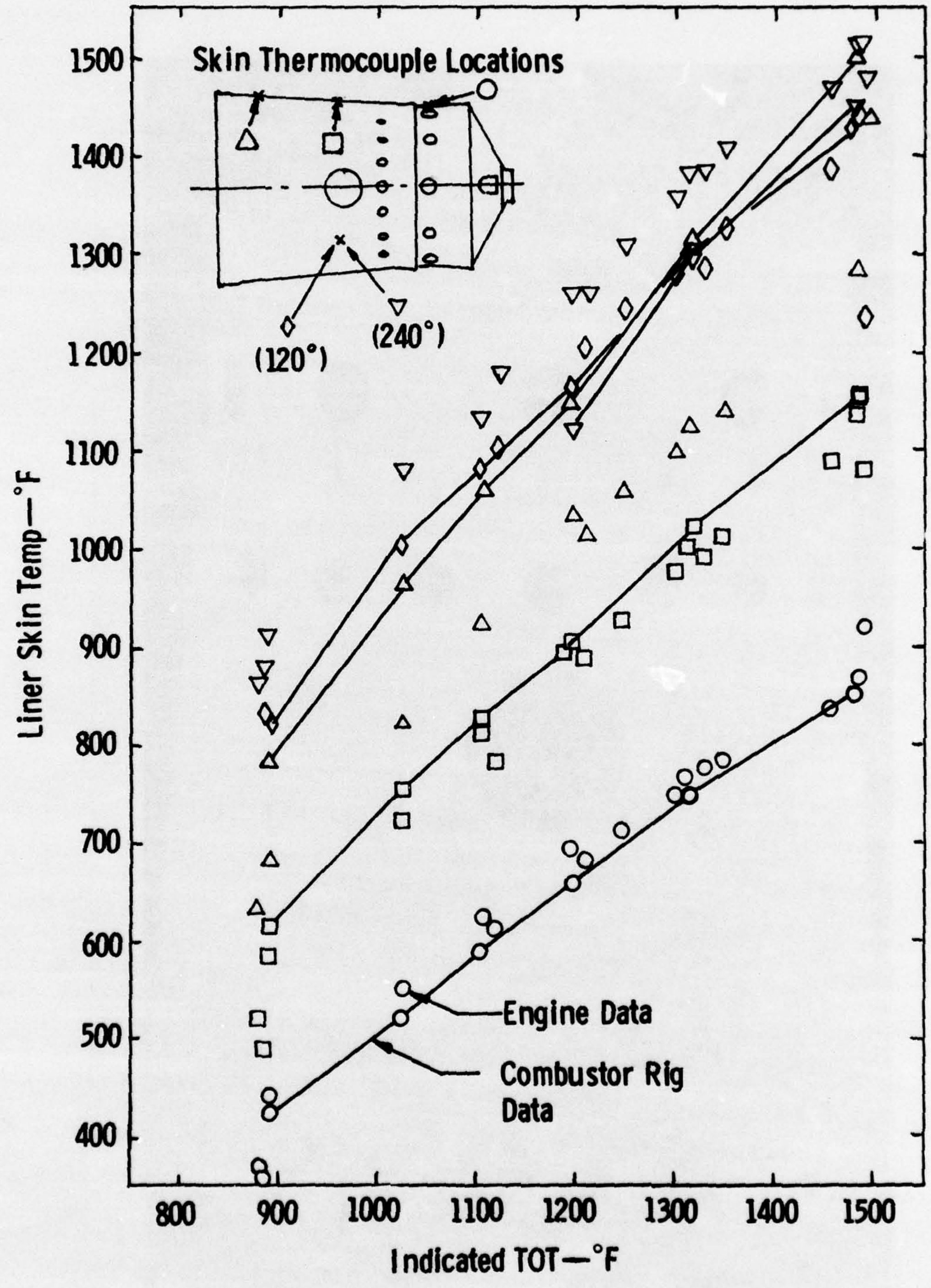

Figure 224. Baseline Liner Rig and Engine Metal Temperatures Comparison.

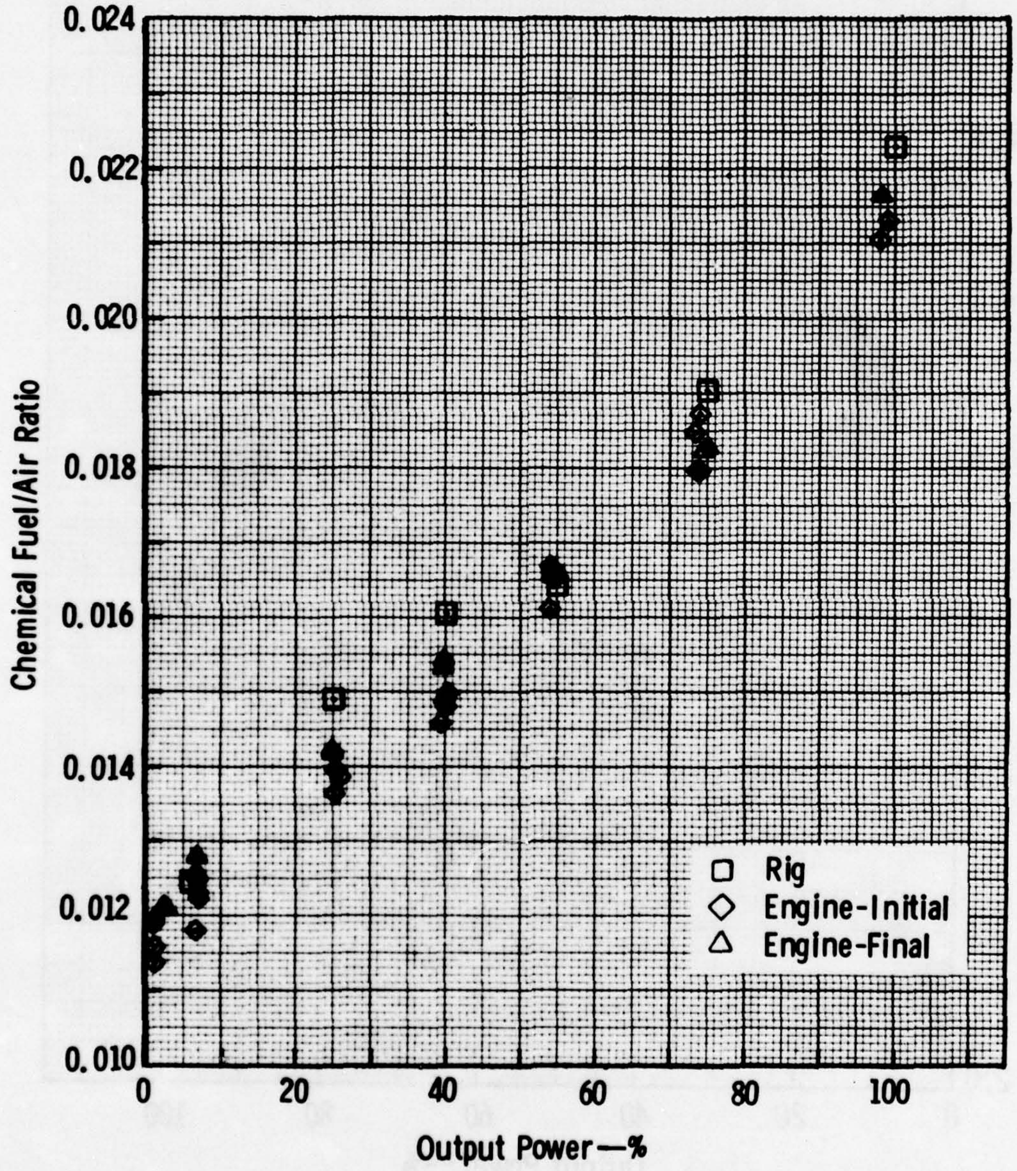

Figure 225. Baseline Liner Rig and Engine Chemical Fuel-to-Air Ratio Comparison.

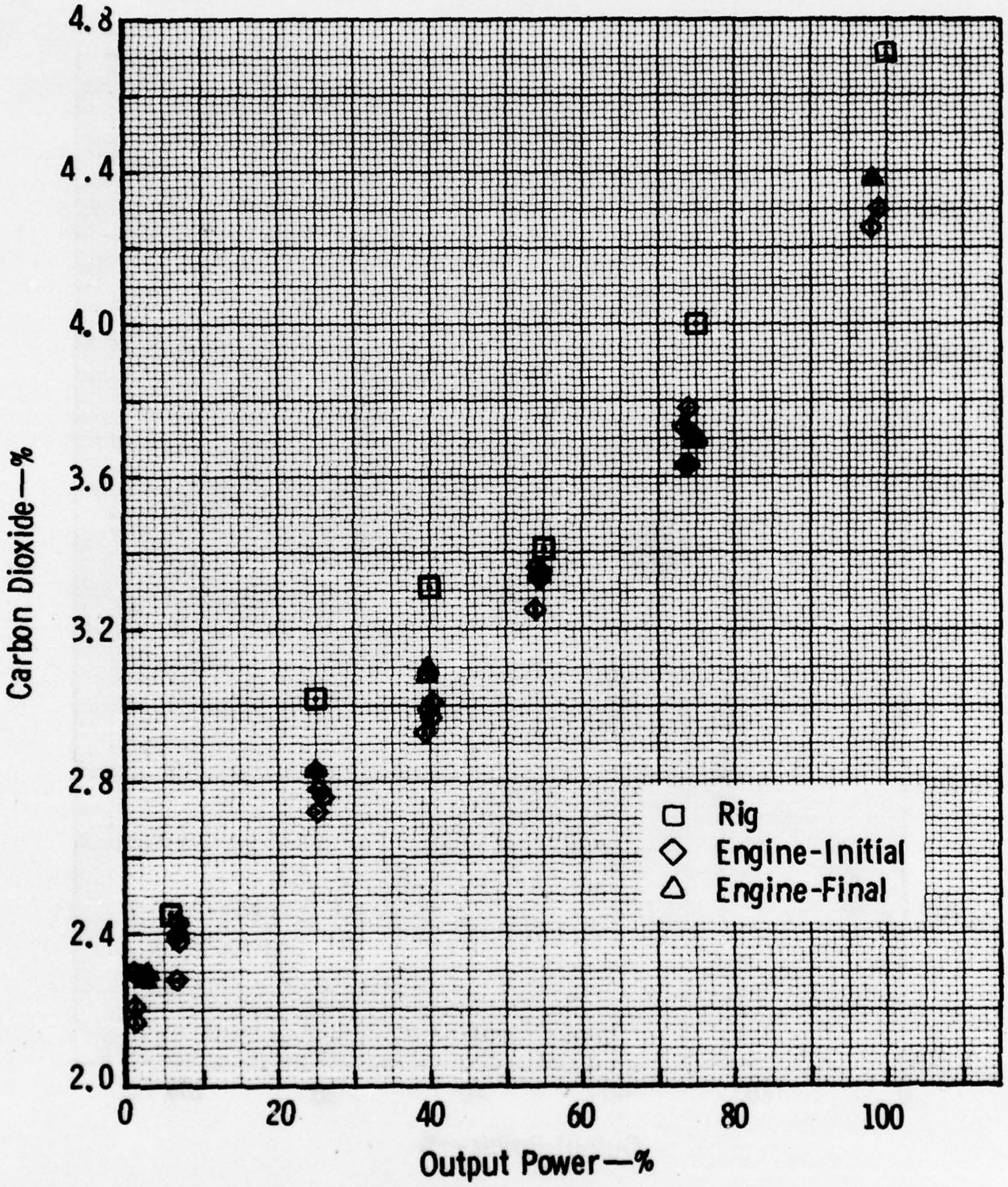

Figure 226. Baseline Liner Rig and Engine Carbon Dioxide Comparison.

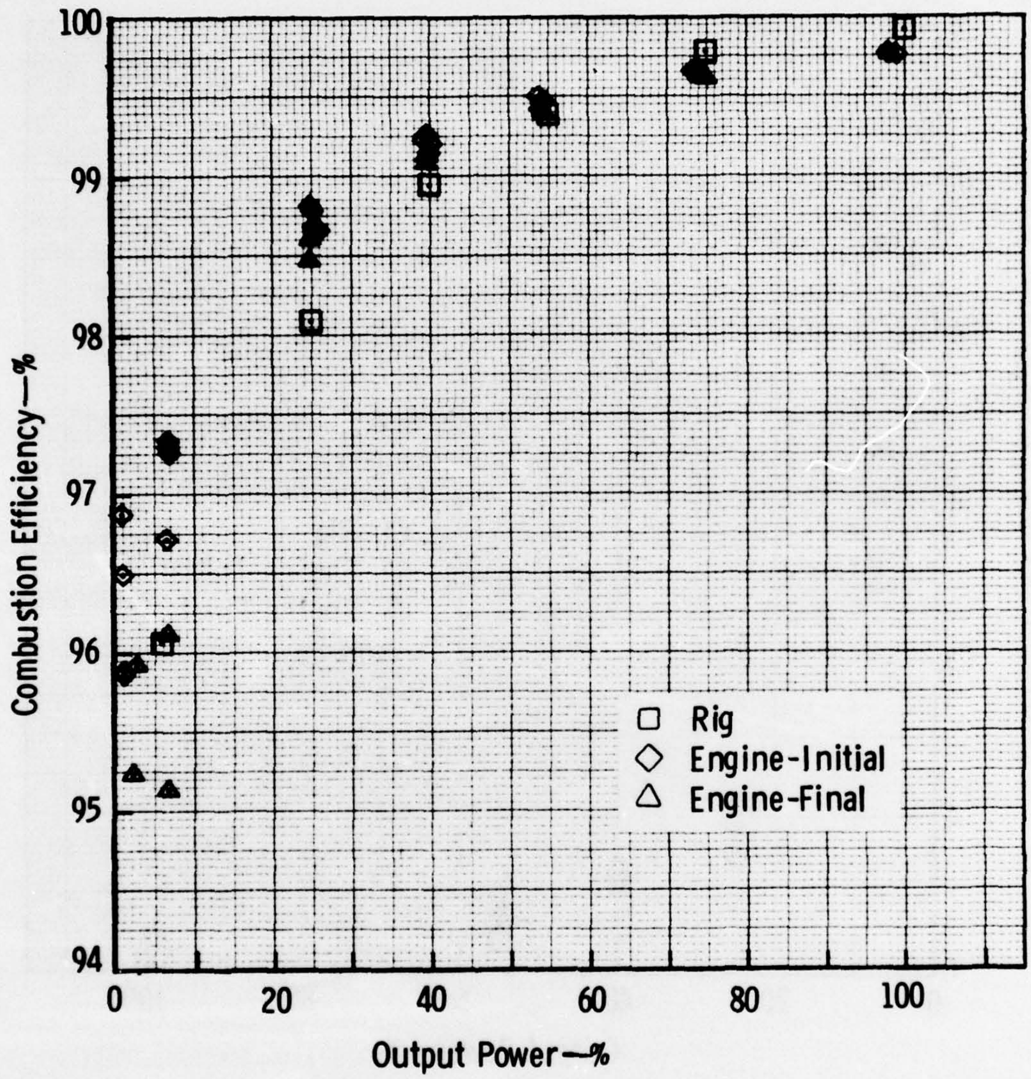

Figure 227. Baseline Liner Rig and Engine Combustion Efficiency Comparison.

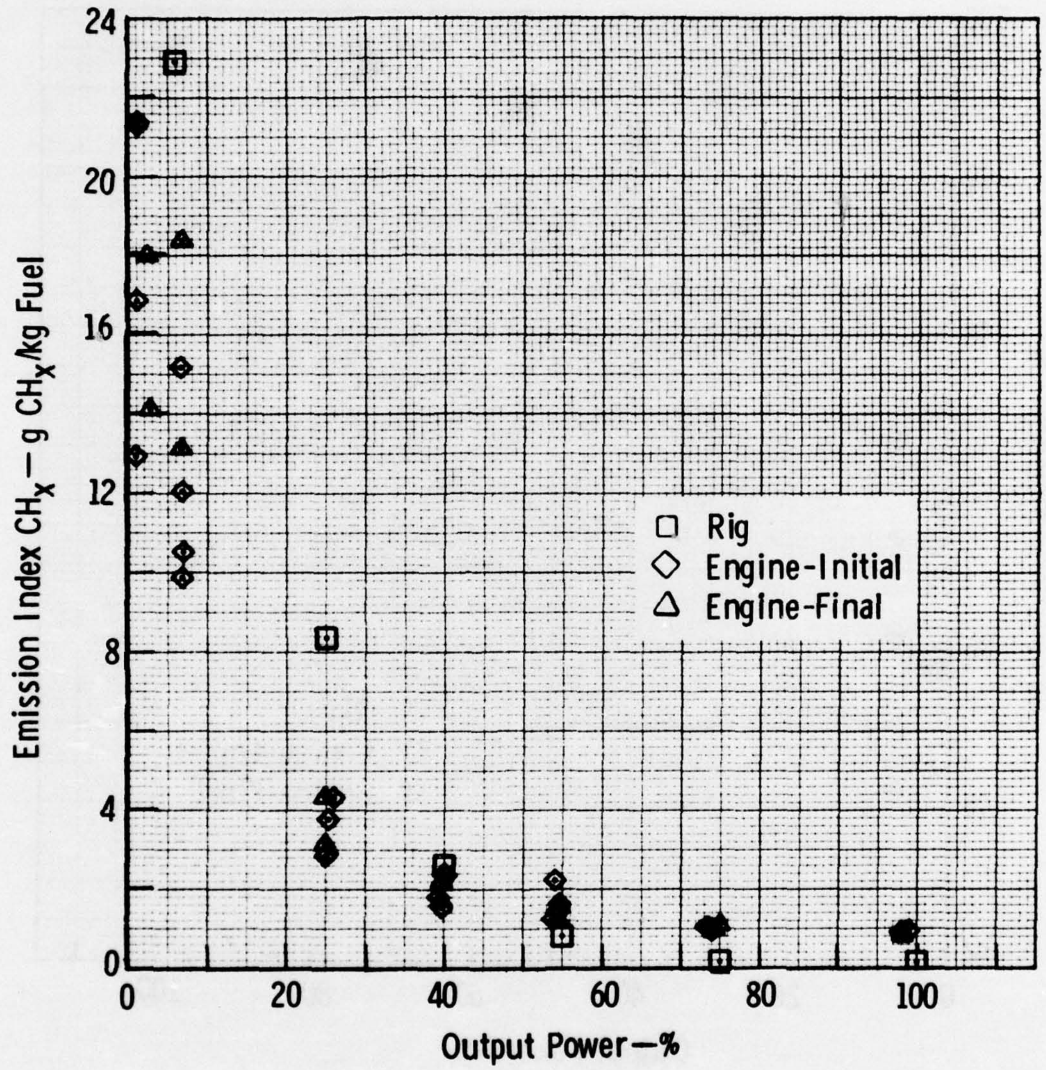

Figure 228. Baseline Liner Rig and Engine Unburned Hydrocarbons Comparison.

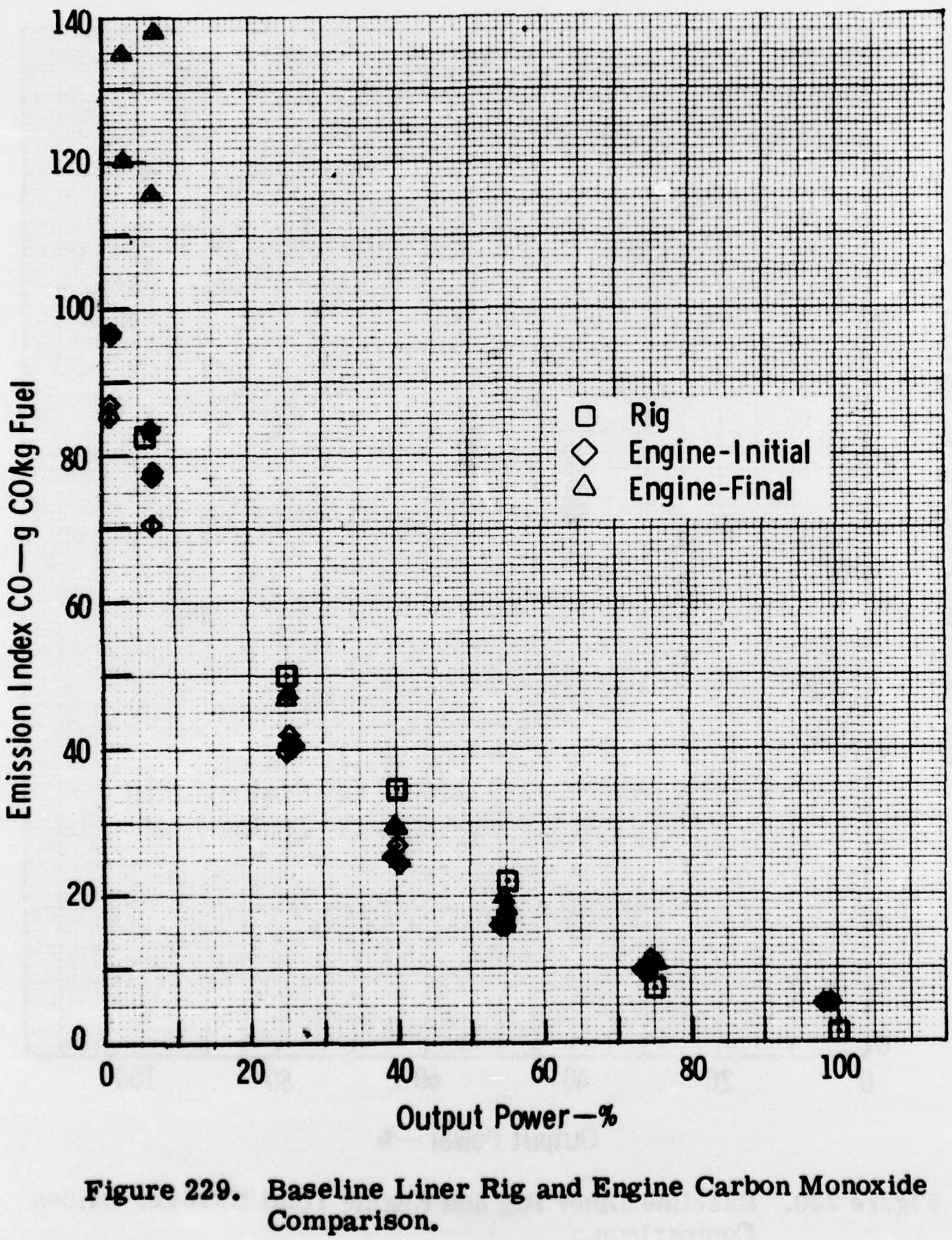

Figure 229. Baseline Liner Rig and Engine Carbon Monoxide Comparison.

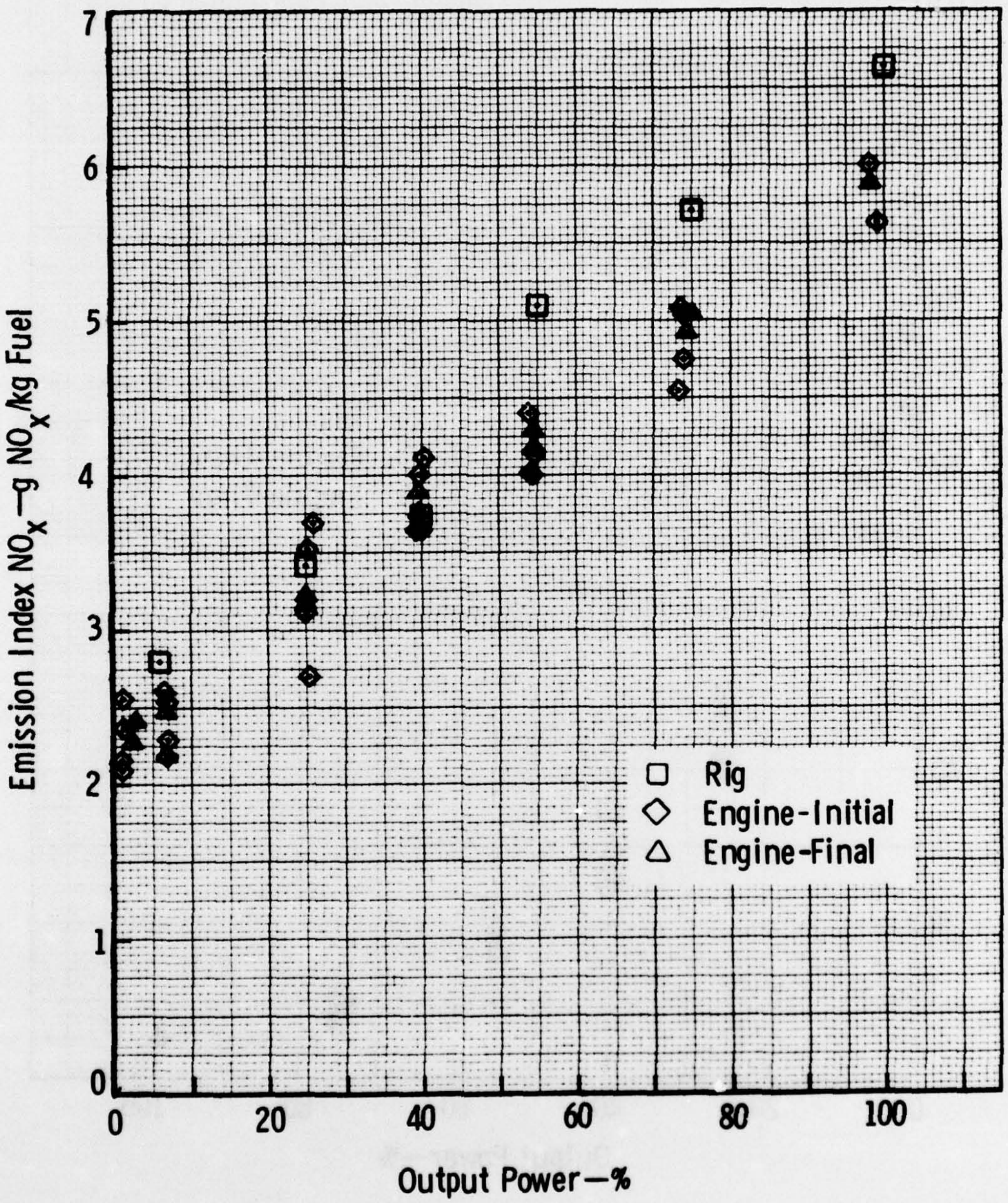

Figure 230. Baseline Liner Rig and Engine Total Nitrogen Oxides Comparison.

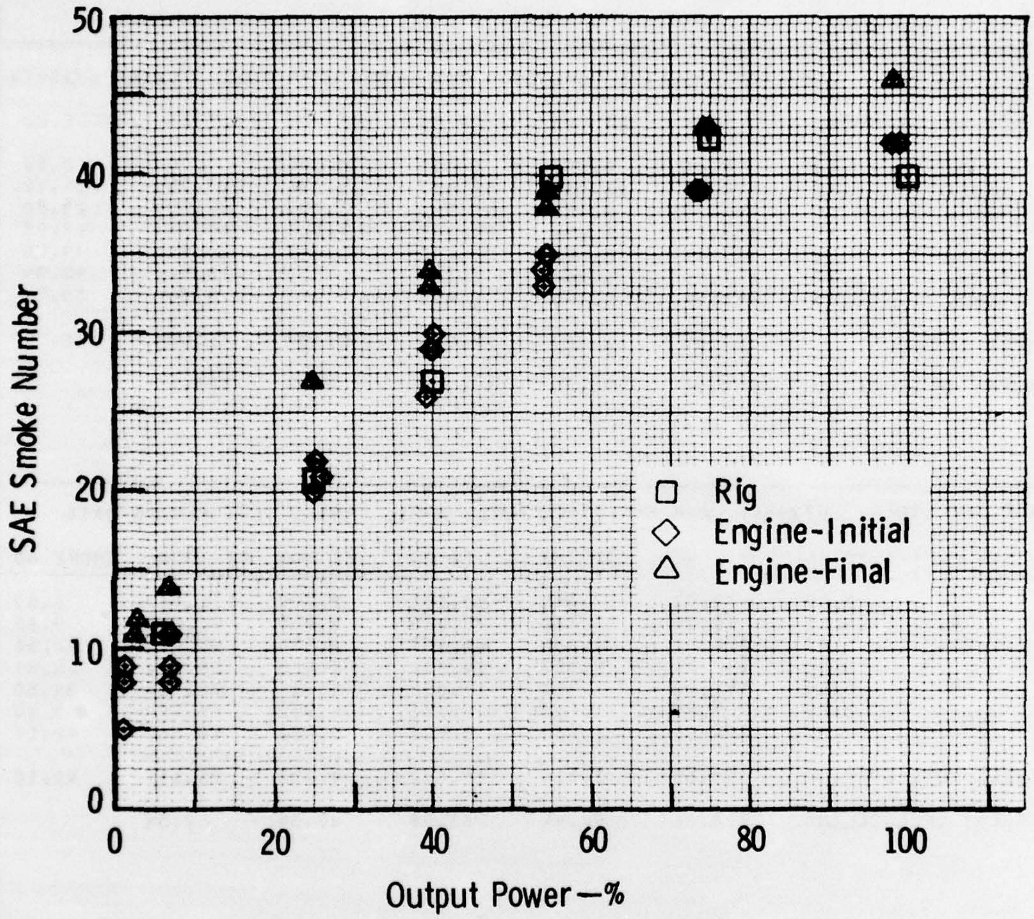

Figure 231. Baseline Liner Rig and Engine Exhaust Smoke Comparison.

TABLE 112. TIME-WEIGHT-AVERAGED LOH DUTY CYCLE EMISSIONS COMPARING BASELINE MODEL 250-C20B COMBUSTOR RIG AND ENGINE TESTS

PRODUCTION MODEL 250-C20B BASELINE COMBUSTOR RIG TEST, JP-4 FUEL TESTED 6-18-74

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
0.	0.00	0.00	0.000	0.000	0.000	0.000	0.00
1333.	0.15	70.36	23.062	90.877	3.076	117.015	11.12
11334.	0.00	107.28	8.521	55.784	3.797	68.102	20.80
1335.	0.15	138.17	2.644	38.187	4.114	44.945	27.03
1338.	0.45	163.11	0.805	23.650	5.447	29.902	39.90
1339.	0.20	211.40	0.163	7.775	6.002	13.940	42.34
1340.	0.05	261.96	0.148	1.452	7.061	8.661	39.91
CYCLE TOTALS		160.06	2.287	23.955	5.397	31.639	42.34
PERCENT OF BASELINE		100.00	100.00	100.00	100.00	100.00	

BASELINE LINER, 6871486, JP-4 REFERENCE FUEL, APRIL ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	70.00	17.354	92.163	2.250	111.767	6.80
6.	0.15	78.00	12.110	78.205	2.359	92.674	9.80
25.	0.00	116.00	3.535	41.387	2.996	47.918	20.50
40.	0.15	143.00	1.959	24.852	3.605	30.416	28.40
55.	0.45	170.00	1.411	17.058	4.514	22.983	34.50
75.	0.20	209.00	1.008	9.337	4.952	15.297	39.20
100.	0.05	262.00	1.080	5.522	5.782	12.384	42.10
CYCLE TOTALS		164.55	2.114	19.542	4.454	26.111	42.10
PERCENT OF BASELINE		102.81	92.44	81.58	82.54	82.53	

BASELINE LINER, 6871486, JP-4 REFERENCE FUEL, JULY ENGINE TEST SERIES DATA

RDG NO	T/T TOTAL	WF	EI CHX	EI CO	EI NOX	EI TOTAL	SMOKE NO
1.	0.00	65.00	18.717	145.267	2.320	166.304	11.00
6.	0.15	69.00	17.713	111.199	2.405	131.317	13.50
25.	0.00	113.00	3.621	47.429	3.184	54.234	27.00
40.	0.15	139.00	1.931	29.907	3.815	35.653	33.80
55.	0.45	166.00	1.497	19.305	4.273	25.075	38.50
75.	0.20	204.00	1.138	10.745	4.942	16.825	42.80
100.	0.05	259.00	0.849	5.391	5.977	12.217	46.10
CYCLE TOTALS		159.65	2.461	23.331	4.401	30.193	46.10
PERCENT OF BASELINE		99.75	107.57	97.39	81.55	95.43	

THE EFFECTS OF THE LOW-EMISSIONS COMBUSTORS ON ENGINE PERFORMANCE

For several areas of engine performance, it is informative to assess the impact of the low-emission combustor performance. In the area of ignition, all of the combustor systems tested had both pilot and main fuel nozzles, but the prechamber liner operated only on the main fuel. Baseline ignition on both the combustor rig and the engine was never any problem. For the modified conventional combustor, ignition on pilot only or on pilot plus main fuel was easily accomplished, but main only ignition was usually not possible. The prechamber liner ignited easily on pilot, main plus pilot, and main only on JP-4 fuel but would not ignite main only on JP-5 fuel.

Both low-emission combustors were ignited at a pressure simulating 25,000 feet altitude on main plus pilot fuel systems, and the prechamber was also ignited on main fuel only. The conditions were 5.45 psia, 0.20 lb/sec air mass flow, 20 lb/hr fuel flow, and 35-40°F inlet temperature. The baseline liner was not tested but is certified to start the engine at 20,000 feet altitude and -65°F ambient temperature on JP-4 fuel.

Engine light-off and acceleration to idle at standard conditions with unity ram was easily accomplished with baseline and modified conventional combustors operating on main plus pilot and pilot only fuel systems, respectively. Engine starting with the prechamber liner having a direct connection of the fuel line to the secondary or main fuel nozzle produced ignition but extremely slow acceleration to idle gasifier speed. It was found that the engine fuel control could not respond properly to the low fuel back pressure from the main fuel nozzle. Inserting a 75 psi pressure relief valve in series with the main fuel nozzle provided adequate back pressure for the fuel control and acceleration of the engine was satisfactory. For JP-5 testing, however, the prechamber combustor required main plus pilot fuels for starting with the pressure relief valve still installed. Once at idle, the pilot could be turned off with all operating modes satisfactorily handled by only the main fuel system.

The baseline combustor experienced lean blowout on the combustor rig at 19-21 lb/hr fuel flows at four different steady-state operating conditions. This corresponded to fuel/air ratios varying from .0038 at idle to .0017 at 100% power pressure, temperature, and air flow conditions. The modified conventional liner exhibited lean blowouts in the range of 10-30 lb/hr from 100% power conditions, depending on the dilution geometry

position. Fuel flow rates were seldom recorded for the prechamber combustor at lean blow out since the rates were below the operating limit of the turbine-type fuel flow meter used. On a temperature rise basis, less than 100°F combustor temperature rises were consistently obtained without blowout.

One fuel rate reading using a Flo-Tron fuel meter recorded 13 lb/hr at 100% power conditions giving a fuel-air ratio of .0011, still with a positive temperature rise.

The Model 250-C20B specification rated engine has a maximum specific fuel consumption (SFC) rating of 0.650 from 88% to 100% power. Within this power range the engine test data from the initial emissions testing on JP-4 fuel produced baseline combustor sfc's over this power range of 0.636-0.621, the modified conventional gave 0.642-0.629 sfc's, and the prechamber liner produced a 0.648-0.634 range of sfc's, all within the specification maximum of 0.650.

During the 113 hours of engine testing of the baseline and low-emission combustors, no combustor related noise, rumble, or vibration beyond that found in the baseline system were experienced. It was difficult to assess whether these low-emission combustors operated any quieter than the baseline system. Also, no excessive turbine erosion was observed after the testing had been completed. The engine was subsequently used on other corporate programs without the turbine section being repaired or replaced.

The only data available to evaluate ingestion tolerance are test results from a corporately funded program which was conducted concurrently with this program. In this test, water of varying volumes was injected in .25 sec into a Model 250-C20 engine inlet. The volume of water was increased in steps of 25 ml until blowout occurred. For the baseline Model 250-C20B combustor system, the combustor blew out above 30 ml of ingested water at idle, 40 ml at 50% power, and 60 ml at 88% power or maximum cruise. Prechamber liner No. 13 was tested and was found to ingest considerably more water than the baseline. The prechamber liner blew out above 150 ml at idle and 100 ml at maximum cruise. Although the modified conventional liner was not tested for ingestion tolerance, a rich primary zone standard liner was tested which would somewhat simulate the low-power dilution setting of the modified conventional liner. This test resulted in a slightly improved tolerance to water ingestion over the baseline liner.

In summary, the low-emission combustors showed improved ignition, lean blowout, and ingestion tolerance over the baseline combustor system, along with equivalent specific fuel consumption, noise and acceleration characteristics. Exhaust temperature profile was worse than from the baseline liner, but the turbine did not show any excessive turbine erosion.

CONCLUSIONS

The significant conclusions resulting from the combustor development and engine testing follow.

COMBUSTOR DEVELOPMENT

Conclusions from the combustor development task are grouped into three areas: general conclusions, conclusions pertaining to the prechamber combustor, and conclusions pertaining to the modified conventional combustor.

General

1. Based on the production baseline combustor exhaust emissions, carbon monoxide accounted for 76% of the time-weighted mass emissions over the LOH duty cycle. Nitrogen oxides accounted for 17% and unburned hydrocarbons were 7% of the total. Thus, to attain the 50% reduction in total emissions, the carbon monoxide emissions required the major emphasis and had to be decreased more than 50% to compensate for the nitrogen-oxide emissions not requiring a 50% reduction.

2. As evidenced by the test data, nitrogen oxides proved to be the most difficult emission constituent to reduce below or maintain at baseline levels and to still obtain 50-60% reductions in carbon monoxide.

Prechamber Combustor

1. The prechamber combustor demonstrated a 60% reduction in total emissions for several configurations but the nitrogen oxides increased substantially above baseline levels.

2. The change from the dual-orifice, pressure-atomizing fuel injector to the airblast fuel injector operating without a pilot nozzle reduced exhaust smoke to very low levels but further increased the already high nitrogen-oxide emissions.

3. Simplex-type, pressure-atomizing pilots as well as impingement- or impact-atomization-type pilots increased CO, CH_x, and smoke, but decreased NO_x emissions. Thus, most prechamber data were recorded with no pilot fuel flow.

4. The prechamber combustor exhibited substantially more lean blowout stability than the baseline combustor system. The fuel-rich prechamber zone provided a very sheltered region for the combustion at low fuel rates. In effect, the swirl-stabilized prechamber becomes a small combustor itself.

Modified Conventional Combustor

1. It was found that the effectiveness of combustor-dilution-zone variable geometry was significantly influenced by the power-level time distribution characterized in the duty cycle. Since variable geometry was used to control the reaction zone conditions, it would be most effective for emission tradeoffs between cycles having or requiring wide variations in power.

2. One configuration of the modified conventional liner did show that 50% total reduction in exhaust emissions could be achieved with no increase in NO_x emissions, but a 50% total reduction plus a 10% reduction in NO_x was never demonstrated.

3. Pilot nozzles in the airblast fuel injector were effective at low powers in reducing CO and CH_x exhaust concentrations with little effect on NO_x or smoke. At mid- and high-power levels, the presence or absence of pilot fuel flow had little effect.

4. With an airblast fuel injector and the variable dilution geometry, the combustor's stability is somewhat better than the baseline system.

ENGINE TESTING

Conclusions from the engine testing portion of the program are grouped into the same three areas: general conclusions, conclusions pertaining to the prechamber combustor, and conclusions pertaining to the modified conventional combustor.

General

1. Both the prechamber and modified conventional combustors completed the engine testing with no damage. The prechamber liner showed that its cooling was insufficient to avoid some thermal distortion in the sheet metal, but this was predictable from the combustor-rig thermal paint test.

2. There was no damage experienced by the Model 250-C20B engine as a result of operating with the low-emissions combustors or with the oil-shale refined fuel in the multiple fuels test.

3. The Model 250 (T63) engine combustor exit temperature pattern is very sensitive to change, and it is quite difficult to obtain a good exhaust profile. Additional development would be required to finalize a good profile for either low-emissions liner.

4. The relationships between combustor rig exhaust temperature patterns and engine combustor exhaust temperature patterns showed only a general similarity. Hot and cold regions in the exhaust annulus were generally the same, but gradients and temperature magnitudes were sufficiently different for the low-emission combustors that reasonable traverse qualities in the combustor rig resulted in quite poor traverse qualities in the engine.

5. Combustor rig and engine exhaust emissions and smoke agreed quite closely, although the exhaust temperature patterns did not. Also, liner metal temperatures measured on the combustor rig agreed well with engine environment measurements.

Prechamber Combustor

1. The prechamber combustor achieved the primary goal of this program of a 50% reduction in total cyclic emissions. Reductions of 50 to 60% were achieved in engine tests. Smoke levels were well below the visible range, with smoke numbers of 10 to 15 measured. The secondary program goal of a 10% reduction in cyclic NO_x emissions was not achieved. NO_x emissions measured in engine testing were 30 to 75% above baseline levels.

2. Engine starting at ambient inlet conditions was easily accomplished with the main airblast fuel system on the prechamber fuel nozzle with JP-4 fuel. When JP-5 fuel was used, the main airblast could not start the engine by itself, and the pilot fuel system had to be used also.

3. Engine exhaust emissions from the prechamber combustor did not change significantly when different fuels were used. Carbon monoxide and unburned hydrocarbon emissions varied only slightly. Smoke was somewhat more sensitive to fuel type, and nitrogen oxides responded in proportion to the fuel-bound nitrogen. Increases in NO_x concentrations when the oil shale fuel was used would indicate that 50-80% of the fuel-bound nitrogen appeared as exhaust NO_x.

4. Fuel nozzle and liner carboning was not a problem when JP-4 or JP-5 fuels were used. A light layer of carbon built up on the inner surface of the prechamber cup, but it was a uniform, hard, thin coating. This coating did not build up beyond a few thousandths of an inch. When the oil shale fuel was used, a considerable soft carbon build up was observed on the fuel nozzle and in the prechamber cup.

5. During the engine running with the prechamber combustor, emission data were recorded which indicated that the flame in the combustor liner was not seated at the expansion point at the prechamber cup exit. During these instances, high smoke was noted, as well as higher than normal CO levels and slightly lower NO_x levels. A considerable hysteresis was involved because, once remedied, the condition could not be repeated. Often, cold start up of the engine favored this condition and JP-5 fuels (both petroleum and oil shale derived) were more prone to the condition than the JP-4 fuel tested.

Modified Conventional

1. The modified conventional combustor system very nearly achieved the emissions goals for the program. The reduction in total emissions ($CO+CH_x+NO_x$) was 48.3% with a goal of 50%, and NO_x increased only 1.4% above the baseline NO_x. The smoke number was below 15.

2. The variable dilution geometry system installed on the modified conventional combustor performed well during all of the testing of the combustor. The actuation was initiated by the test operator via a control panel switch, but a speed switch could have been used to make the system automatic.

3. For the two-position variable-dilution geometry, the separation of the hole configurations for the two settings permitted independent tailoring of both emissions and exhaust temperature pattern.

RECOMMENDATIONS

The emission reduction technology demonstrated in this program has potential application for can and can-annular combustors in aircraft gas turbine engines. It is recommended that the following abatement concepts be used for reducing constituent emission concentrations.

For reduction of carbon monoxide and unburned hydrocarbons:

- Substitute convection cooling or reverse-flow film cooling for downstream film cooling around the primary zone.
- Increase the flame temperature by richening the primary zone. This can be accomplished either with a fuel rich design, as was done with the prechamber liner, or by variable geometry, as done with the modified conventional.
- Increase the combustor volume, as was done in the prechamber.
- Concentrate the fuel spray in the center of the liner at low power by using substantial amounts of pilot nozzle flow, as was done with the modified conventional nozzle.
- Delay the dilution air to provide more intermediate zone (high temperature) volume.

To reduce nitrogen oxides:

- Reduce the flame temperature by leaning the primary zone at high power with variable geometry.
- Increase pilot fuel flows at low power levels in an already rich environment in the prechamber.

To reduce exhaust smoke:

- Inject fuel with a well-designed airblast nozzle and a reasonably high liner-pressure drop to have sufficient energy in the air for good atomization and mixing.
- Minimize or eliminate pilot fuel flows in fuel-rich primary prechamber combustors.

Although significant emission abatement technology was demonstrated in this program, a continuing and expanded effort is recommended to:

- Further develop and apply some of these concepts.
- Investigate new concepts, which might lend themselves more easily to a given installation.
- Study the problems encountered in this program to better understand their causes and develop their solutions.

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LIST OF SYMBOLS

A	Fuel constant used in gas analysis equations
B	Fuel constant used in gas analysis equations
C	Fuel constant used in gas analysis equations
C	Concentration, ppm
CH_x	Exhaust concentration of unburned hydrocarbons, ppm (C_1 equivalent)
CO	Exhaust concentration of carbon monoxide, ppm
EI	Emissions index, gm emission/kg fuel burned
F/A	Fuel to air weight ratio
fr	Volume fraction
Hg	Mercury
NO_x	Exhaust concentration of total nitrogen oxides, ppm (NO_2 equivalent)
η_b	Combustion efficiency